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Effects of various solar spectra on photovoltaic cell efficiency and photonic hydrogen production

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ABSTRACT

In this study, an experimental setup is built to investigate the effects of different solar spectra on the PV (photovoltaic) cell efficiency and hence on photonic hydrogen production. A solar simulator is used as an artificial light source, and a spectrometer, an irradiance meter and temperature sensors are utilized for experimental measurements. In addition, potential losses, such as transmittance and reflectance within the system are determined, and the effects of different type of optic filters on solar spectra and the system are investigated and comparatively assessed. The results of this study show that there is an important efficiency decrease when a reflecting mirror for solar simulator is used, and that lower wavelength solar spectrum brings higher PV cell efficiency and hence hydrogen production. Furthermore, solar spectra can be divided for multiple subsystems to efficiently utilize solar energy.

Introduction

Solar irradiation is the most abundant source of energy on earth. The majority of physical and chemical reactions encountered on earth, including photosynthesis and water and air circulation in the atmosphere, are a direct or indirect result of solar radiation. In order to effectively utilize solar energy, the first issue is the low density of solar radiation per unit of earth surface. The solar radiation intensity on earth surface changes between 0.4 and 1 kW/m^2 [1].

Solar based hydrogen production methods emerge in this century where the photo electrochemical hydrogen production option plays an important role. [2]. In this regard, the performance of photo electrochemical systems is essentially influenced by several parameters, for example, the band gap energy of catalysts and the spectrum of solar radiation, factors that must be considered in the selection of photocatalysts and photoreactions [3]. The DoE's (Department of Energy) projected solar-to-hydrogen conversion efficiency is according to Getoff [4] in the range of 30–40% for 2025. According to Dincer and Zamfirescu [5], it appears that the decisive factor for success of large-scale solar hydrogen production is the synergistic integration of key technologies and multiple valuable product generation while keeping the system simple. Because, if multiple products are generated, and hence the economic viability of the system is enhanced while the requirement of increased hydrogen production efficiency becomes less stringent.

Solar cells are basically made of semiconductor materials which can utilize mostly the visual light spectrum to generate electricity. When solar radiation with wavelengths of 380 nm–750 nm hits the material with sufficient energy, the electrons are ignited from their weak bonds and generate an

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electric current. Therefore, with existing solar cells, the unused ultraviolet and infrared wavelengths are not efficiently converted into electricity but rather absorbed as heat which also decreases the efficiency of the cells. As discussed in the numerous studies in the literature [6–9], an increase in PV cell temperature affects the efficiency negatively.

Note that actual cell efficiency η_c can be written as the difference between the generator efficiency η_g at T_{NOCT} nominal operating cell temperature (NOCT) and the temperature induced efficiency drop δ_n [8]:

$$\eta_c = \eta_g - \delta_n$$

with the temperature induced efficiency as

$$\delta_n = \beta_{ref} \cdot (T_c - T_{NOCT}) \cdot \eta_g$$

where the value of temperature coefficient β_{ref} is usually in the range of 0.3 and 0.5%/°K, T_c is the cell temperature.

Potentially, the solar spectrum is better harvested if, instead of converting the concentrated radiation in high temperature heat, one generates hydrogen using high energy spectrum, one generates electricity with photovoltaic arrays using middle spectrum photons and one converts only the high temperature heat associated with long wave photons to electricity using Rankine cycle. Hence, utilizing this waste heat as a useful output and cooling the PV cell temperature would enhance both the PV cell and integrated system efficiency.

Spectral splitters can be devised using an appropriate combination of optical filters. Various dielectric coatings can be deposited in thin films to generate selective filters or selective reflective surfaces [10]. Faine et al. [11] indicated in their research that effects of variations in solar spectral irradiance depend on the bandgap of the device as well as on the number of junctions. Turbidity and air mass fluctuations affect the performances of high-bandgap devices more than those of low-bandgap devices. However, water-vapor fluctuations have very little effect on high-bandgap devices compared with low-bandgap devices. Gottschalg et al. [12] showed that one can distinguish between two effects: a primary effect that results from variations in the total irradiance in the spectrally useful range of the device, and a secondary effect observed in double junction devices that is related to details of device structure. Nagae et al. [13] demonstrated that the FOF (field output factor) of a-Si PV modules significantly depends on the variation of the incident solar spectrum. In their research, for stacked a-Si PV modules, little influence of both APE (average photon energy) and module temperature on FOF was observed Minemoto et al. [14] investigated the effects of spectral irradiance distributions on the outdoor performance of amorphous Si//thin-film crystalline Si stacked photovoltaic (PV) modules installed at Shiga-prefecture in Japan. They found out that more than 95% of annual total spectra were blue-rich compared to AM (Air mass) 1.5 standard solar spectrum.

Nann and Emery [15] indicated in their experimental study that efficiencies of amorphous silicon cells differ by 10% between winter and summer months because of spectral effects only. Since the PV performance is dependent on solar spectra in the field, structure of PV has to be designed so as to obtain the most efficient performance in natural sunlight at outdoor. On the other hand, currently AM 1.5 standard solar spectrum is utilized to measure nominal power output of PV modules which is not exactly same with actual spectral irradiance. In order to evaluate the performance of PV modules, the performance measurement under actual spectral irradiance distribution is essential where PV modules are installed. This enables a higher accuracy of predicting power output from PV modules, hence increasing the reliability of PV based electrolyzer systems. Using the energy storage alternatives, electrolyzers load tracking capabilities could be increased.

Power conversion efficiency and overall output power of the solar cells change with temperature and solar irradiance level. Temperature rise really affects the PV module performance ratio (PR) by producing contour graph for the temperature impact towards single-crystalline and amorphous silicon modules [16]. Ya'acob et al. [17] conducted an experimental research for the effect of temperature elements for PV array with tracking and concentrating features installed in the tropical ground condition. The temperature segment covers ambient temperature and surface and bottom temperature for three types of PV generator systems, namely, Fixed Flat (FF), Tracking Flat (TF), and Concentrating PV (CPV) generators. Kim et al. [18] emphasized that with a convenient method of cooling PV module by means of heat dissipation process using fins, interestingly, the energy efficiency from a common PV module usually falls at a rate of 0.5%/°C and it can be increased due to the drop in surface temperature especially on the highest heated portions of PV cell and ribbon where all means of cooling approach come into the picture.

In this paper, an experimental setup is built to measure and investigate the effect of different solar spectra on total PV cell efficiency and hydrogen production by using solar simulator as a light source and a spectrometer, an irradiance meter, a reference potentiostat, temperature sensors as measurement devices. The PV cell is connected to a photo electrochemical reactor. Various types of losses such as transmittance and reflectance within the PV cell and before the PV cell are defined and effect of reflecting mirrors, filters and glassing are comparatively assessed.

Experimental setup

The measurements are taken in the CERL Laboratory of University of Ontario Institute of Technology (43.9448° N, 78.8917° W) under solar simulator (OAI Trisol TSS-208 Class AAA) with an irradiance of 800–1100 W/m^2 (Fig. 2b). The outputs from the PV module were measured by a Potentiostat/Galvanostat/ZRA (Gamry Instruments Reference 3000) (Fig. 1a). As shown in Fig. 5a to analyze the spectral irradiance distribution, solar spectra with the wavelength range of 350–1000 nm were recorded by a spectrometer (Ocean Optics Red Tide USB 650) (Fig. 1b). PV surface temperature is measured with surface temperature sensor (Vernier STS-BTA) (Fig. 3a) and ambient temperature is measured with probe temperature sensor (Vernier GO-TEMP) through a data logger unit (Vernier LabQuest) (Fig. 3b). A pyranometer (Vernier PYR-BTA) (Fig. 2a) and irradiance meter were installed with same angle of PV modules to measure total global irradiance. The utilized PV