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Solar spectrum management for effective hydrogen production by hybrid thermo-photovoltaic water electrolysis

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ABSTRACT

Solar Hydrogen is one of the potential key technologies to fuel human's progress. Optimizing the utilization of sunlight to produce Hydrogen using a hybrid thermo-electrolysis system is useful to promote such technology to broad deployment. Theoretically, it was found that a proper sunlight utilization management by an optimized spectral splitting of the solar spectrum between heating water to produce steam on the one hand and producing electricity via photovoltaic cell to energize the steam electrolysis on the other hand leads to an efficient sunlight to Hydrogen conversion. We report in this theoretical work that 82% sunlight to Hydrogen conversion efficiency can be accomplished from the proposed optimized hybrid thermo-photovoltaic system that employs a 90% efficient solar-thermal convertor. Additionally, it was found that for the proposed optimized hybrid system a quadratic enhancement for both the photovoltaic conversion efficiency and the net solar to hydrogen conversion efficiency can be obtained from employing more efficient solar to thermal convertor. Unlike the previous works, which have handled the optimal photon management in the hybrid thermo-photovoltaic system, our proposed optimization method accounts thoroughly the major losses in the photovoltaic conversion like the thermalization process and the limiting fill factor of the PV cell. Therefore, the methodology and the results of this work are more realistic and could be a useful recipe for an optimal sunlight spectrum management for an effective solar-hydrogen production, which could thrive as a reliable carbon-free-source of energy.

1. Introduction

Solar energy presents the prime source of energy for life on earth, and for humans' progress, in particular. It is not only that the sunlight conversion into electricity or heat is essential for various applications, but also a reliable storage of the sunlight converted energy is highly useful since many applications require storing the harvested solar energy to meet certain consumption pattern. For instance, transportation and many other applications that operate at night or cloudy conditions require converting and storing the solar energy for later convenient consumption. Basically, the solar energy, after being converted, can be stored either thermally or

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chemically. The thermal storage utilizes the ability of any thermal mass to store energy as sensible heat; like rising the temperature of water in a thermally isolated storage tank, which is widely applied method because of the water high specific heat and abundance; or storing the sunlight produced heat energy in the form of latent heat using phase change materials like paraffin and some special kinds of salts [1]. On the other hand, chemical storage of sunlight is found in different and various applications. Currently, the most common chemical storage of sunlight energy is achieved by the rechargeable batteries such as the lead batteries which are charged during daytime from arrays of photovoltaic PV cells. However, such rechargeable batteries have major drawbacks; for instance, they are relatively expensive and sensitive to the operation and storage conditions, which make them having relatively short life service and limited application.

One great potential for the chemical storage of energy is to store pure Hydrogen gas in special cylinders. Naturally, Hydrogen does not exist in its molecular form because of the instant combustion with the surrounding Oxygen; nevertheless, this can be realized by splitting water chemically using the well known electrolysis technology [2,3]. The electrical power that is needed to drive the water electrolysis could be obtained from various sources; the solar energy, which is the prime renewable energy source; is the most promising since it is globally available with immense quantities. However, the known sunlight to electricity conversion technologies are costly and relatively have low conversion efficiency that is below 25 percent for most of the available market photovoltaic cells. Such cost/efficiency problem presents a serious limitation on most solar conversion technologies from being widely applied and thrives, and the solar-Hydrogen technology is not an exception here.

Another known approach of utilizing the sunlight to produce Hydrogen is the water thermolysis [4], which depends solely on heating water to extremely high temperatures that exceeds 2500 K using. Such process is attractive since the conversions technologies of the concentrated sunlight to heat are well established with reasonable efficiencies. However, there are major practical issues; special high-temperature materials that are chemically stable and mechanically durable against thermal stresses are required to build a thermolysis reactor. Additionally, the two gas products from the thermolysis process are not separated to be usefully and safely collected; unlike the water electrolysis, where the two gas products are produced and collected at two different sides. Porous ceramic membranes can be used to separate the thermolysis gas products; nevertheless, there is always risk of recombining explosively since they are generated at the same hot spot.

Apparently, a practical solution for the above challenges is by devising a hybrid thermo-photovoltaic system which heats water to produce hot steam as the raw material for the electrolysis cell and, simultaneously, produces electricity using photovoltaic cells in order to energize the steam electrolysis process [5–10]. Usually, most of the losses that associate the photovoltaic conversion of sunlight to electricity are wasted in the form of internal heat inside the cell; this lowers the efficiency and adds an engineering burden for regulating the PV cell operating temperature in order to maintain acceptable performance; specially, if the PV cells are used in the concentrated sun regime as it should be the case for the hybrid thermal-photovoltaic system in order to realize high water temperatures and to reduce cost by using less area of the expensive PV cells.

As a matter of fact, the higher is the temperature of the water (steam) the less electricity is needed to run the electrolysis process; therefore, it would be advantageous if the solar energy that is lost (or will be lost, in a better configuration as will be discussed below) as heat in the PV cell can be utilized to pre heat the water by facilitating a heat exchange between the water and the heated PV cell. Such energy management helps not only to prevent the overheating of the PV cell, but also produces more Hydrogen since the electrolysis becomes more efficient with hotter water (steam). However, such configuration has drawbacks; for instance, in order to transfer heat from the heated PV to water, the last should come into contact with the PV cell, which is not desirable in practice. Besides, the PV cell, though overheating is controlled, should be maintained at reasonably high temperature, i.e. higher than the temperature of the supplied water, in order to facilitate effective heat exchange; which again causes performance and lifespan issues of the PV cell.

A better configuration is to optimally partition (i.e. by spectral splitting) the solar spectrum properly from the very beginning such that a minimum cell heating can be obtained by supplying the PV cell with those photons from the solar spectrum that exhibits high photovoltaic conversion efficiency, therefore, producing more electricity and less heating for the PV cell. Practically, a dielectric multi-layer interference beam splitter can be employed to split and manipulate the solar spectrum such that one spectral part from solar spectrum is supplied to the PV cell to generate electric current that drives the electrolysis process; whereas, the remaining part of the solar spectrum can be used to heat the water. This management of the solar spectrum for water splitting is a known approach [6,11–17] but, to the best of our knowledge, it was not optimized thoroughly by accounting the major losses that associate the photovoltaic conversion which effectively reduces the efficiency of the overall hybrid thermo-photovoltaic system. For example, the scheme proposed by Licht in Ref. [6] suggests that the solar spectrum band that extends from the shorter ultraviolet UV wavelength to the wavelength ($\lambda_{max} = 532$ nm) where the solar power intensity is maximum is supplied to the PV cell in order to produce electricity; whereas, the remaining part of the solar spectrum that starts from $\lambda_{max} = 532$ nm to the end of the solar spectrum in the infrared IR region is utilized to directly heat water; that is, the proposed scheme uses the none absorbed longer wavelength photons of the sunlight that are beyond the cutoff wavelength λ_G of the PV cell to pre heat water, whereas, the other photons with wavelengths that are shorter than λ_{max} are converted to electricity by the PV cell to drive the steam electrolysis. Logically, this management of the solar photons sounds useful but not optimal for two reasons. First, the scheme have treated one factor of the spectral mismatch between the solar spectrum and the spectral response of the PV cell which comes from the none absorbed photons but did not account the thermalization losses; which comes from producing hot electors by the absorption of the high energy photons, like those in the UV region. Usually, those hot electrons lose their excess energy in the form of phonon emission and, therefore,