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Energetic and exergetic investigations of an innovative light-based hydrogen production reactor

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ABSTRACT

In this study, it is aimed to thermodynamically study and experimentally test a continuous type hybrid photoelectrochemical hydrogen production system. The hybrid system considered in this study is capable of enhancing solar spectrum utilization via the combination of photocatalysis and PV/T. In addition, the system eliminates the electron donor requirement of photocatalysis by employing photoelectrodes. Which, as a result, risk of potentially harmful pollutant emissions is reduced. In this study, the present system is investigated in electrolysis operation under three different inlet mass flow rates (0.25, 0.50, and 0.75 g/s). The experimental results are compared to the thermodynamic model outputs. Parametric studies are conducted by changing the inlet mass flow rate from 0 to 1 g/s. The present experimental results suggest that the highest hydrogen production rate is observed at 0.75 g/s inlet mass flow rate, which is 2.43 mg/h. The highest energy and exergy efficiencies are calculated at 0.25 g/s, which are 36% and 32%, respectively. Furthermore, thermodynamic model outputs are confirmed to have a good agreement with the experimental results.

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Introduction

As the worldwide population and their living standards drastically increase, it gets more and more difficult to meet the ever-increasing global energy demand in an affordable, clean, reliable, and sustainable manner [1]. Fossil fuels are not expected to keep up with the increasing global energy demand for many reasons including their limited and non-homogeneous resource distribution [2]. In addition to this disadvantage, fossil fuel prices are anticipated to keep increasing as easily accessible fossil fuel resources are used up, the remaining reserves get more difficult to reach, and it gets more challenging to extract fossil fuel from the remaining reserves [3]. Besides the resource cost and reliability issues, fossil fuel based energy systems have serious environmental impacts, e.g., greenhouse gas (GHG) emissions [4]. Climate change is a serious threat to millions of people worldwide and

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many authorities are planning to significantly reduce CO_2 emissions by eliminating or minimizing fossil fuel use [5].

Sustainable energy systems take advantage of clean energy sources in an efficient manner [6]. For that reason, these systems can address the issues related to global energy issues by meeting the worldwide energy demand with zero or negligible harm to the environment [7]. Sustainable energy systems have considerable advantages from environmental, energetic, economic, and society perspectives. A sustainable energy system has to have the following characteristics: (i) minimum or zero negative environmental or societal effect; (ii) zero or negligible depletion of natural material and energy resources; (iii) capability to meet the current and future generation's energy demand; (iv) reliability, affordability, availability, and efficiency; (v) protection of air, land, and water; (vi) zero or negligible net GHG emissions; and (vii) capacity to meet current population's energy requirements without risking the future generations' resources [8].

Hydrogen is a vital energy carrier to be employed in sustainable energy systems for the reasons that could be listed as (i) production, conversion, and end use of hydrogen energy systems are highly efficient; (ii) when clean energy and material resources are used, production, conversion, and end use of hydrogen energy systems does not pose a risk to the environment or health of living beings; (iii) hydrogen is abundant, it exists in many forms and can be extracted from a variety of material resources; (iv) there are many alternatives to store hydrogen (e.g., in gaseous, liquid, or solid phase storage); (v) hydrogen can be distributed to prolonged distances with minimum loss; (vi) hydrogen can be converted to other forms of energy in more methods than the existing alternatives; (vii) hydrogen has higher HHV and LHV than the most of the conventional fossil fuels. On the other hand, most of the existing hydrogen production systems are not well established, hence they have high hydrogen production costs and/or low system efficiencies [9,10].

Furthermore, hydrogen is a greatly promising energy carrier which could potentially turn into one of the main components of the future sustainable energy systems. Hydrogen can be produced from a variety of energy and material resources and be converted to many different forms of energy (e.g., electricity, heat, chemicals, etc.) in a clean manner with minimal or zero greenhouse gas emissions. In order to become truly sustainable, production, conversion and end use of hydrogen should be clean, affordable, reliable, and accessible. For this reason, efforts are required to expedite the implementation of hydrogen energy systems.

In the recent literature, there are many publications on hydrogen energy systems, especially focusing on innovative ways to produce hydrogen in efficient, affordable, reliable, and clean manners. The literature states that the existing hydrogen production options could be used alone, or combined with other alternatives for sustainable hydrogen production. Even though fossil fuel based hydrogen production is not considered as sustainable, the fossil fuel based methods can be used during transition to clean and innovative hydrogen production technologies [11].

There are many existing hydrogen production methods, in many stages of research and development and market introduction. Each one of these methods has certain advantages and disadvantages. Therefore, choosing the most appropriate hydrogen production method is quite challenging. This decision should be made based on system characteristics and existing conditions such as resource accessibility, affordability and reliability, geographic location, population and climate characteristics, and compatibility with the existing energy infrastructure, etc. It should be noted that fossil fuels are anticipated to keep playing an important role in the existing energy infrastructure, about 25–30 TW of energy demand is expected to be met by fossil fuels for at least a few centuries [12]. Subsequently, they are estimated to be used as the primary hydrogen resource when the necessary infrastructure is designed, tested, developed, and built to produce hydrogen from sustainable energy systems in large scales [13,14].

As a renewable and abundant energy source, solar energy has a potential to turn out to be a promising resource to support sustainable energy systems to meet the ever increasing worldwide energy demand, including sustainable hydrogen production requirements. Worldwide annual energy consumption can be met by the energy content of about 30 min of solar irradiation reaching to the Earth's surface [15]. Most of the solar-based energy systems have relatively small scale up costs compared to conventional fuel based ones, which is another advantage of solar energy [16]. Despite these substantial advantages, solar energy has certain drawbacks such as its intermittent characteristics, i.e., because of day and night cycles, cloudy and hazy days, etc., the amount of solar energy reaching to the Earth's surface is not continuous and steady. This issue could be tacked by storing solar energy in other forms, such as hydrogen in order to make it accessible without any undesirable interruption. Hydrogen is a chemical fuel, which makes it a good alternative to store solar energy in an efficient manner. Hydrogen also has high energy storage capacity and its transportation is easier with minimal losses compared to other energy storage mediums [17].

Water splitting is a promising method to convert solar energy into hydrogen since water is an abundant, reliable, accessible, and easily manageable material resource of hydrogen. The minimum and maximum energies of a photon in the visible light portion of the solar spectrum is around 1 eV (100 kJ/mol) and 3 eV (300 kJ/mol), respectively, which is satisfactory enough to produce hydrogen via water splitting [18]. Solar-based hydrogen production can be done through a variety of methods, from artificial photosynthesis, PV-based electrolysis, and photoelectrolysis to thermochemical, photocatalytic, and photoelectrochemical (PEC)-based water splitting. Each one of these methods has specific advantages and disadvantages. However, PEC-based hydrogen production has some certain advantages which makes it a promising option among the existing alternatives, such as affordability, reliability, environmental impact, and ease of access [19]. The general form of solar energy powered water splitting reaction is written as

$$2H_2O \xleftrightarrow{sunlight} 2H_2 + O_2 \quad \Delta G^\circ = 238\,\mathrm{kJ/mol} \tag{1}$$

In the literature, there is a variety of published books [18,20,21] and review studies [22–24] explaining the theory behind photoelectrochemical hydrogen production, electrochemical reactions, photoreactor design, and photoactive

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