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Sustainable assessment of solar hydrogen production techniques

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ABSTRACT

This study addresses some technical issues related to solar hydrogen production methods. In this regard, exergy-based environmental and sustainability parameters are applied to an electrolysis process for hydrogen production. Accordingly, the environmental destruction index is found to be 0.16 while exergetic benign index is calculated as 6.30. While the exergy efficiency increases from 10 to 90%, the sustainability index rises from 0.01 to 8.1. Thus, solar hydrogen production should be used for practical applications because of higher exergetic sustainability potential and lower environmental destruction index.

1. Introduction

Energy becomes a vital key element for the world in last 40 years and stands in the middle of a triangle that has sides of nature, society and economy. While the population increases over than 2%, the energy demand of the wealthy society including 25% of the world's population consumes 75% of the world's energy supply [1]. Currently, the world consumes about 85 million barrels of oil and 104 trillion cubic feet of natural gas per day, releasing greenhouse gases (GHGs) that cause to global warming as told [2]. The world has begun to seek the clean energy sources as the fossil fuels reserves decrease. Besides, the growing interest towards green energy is also started because the green energy appears to be sustainable and clean energy source as an alternative to fossil fuels. Considering all these important reasons, it can be told that it is necessary to use the thermodynamic systems that have high efficiencies which are integrated to the sustainable energy sources. In order to reveal if a thermodynamic system is efficient or not, exergetic performance of the system has to be defined. Also, the other important point for the systems is sustainability. Sustainability supplies local and national authorities to incorporate environmental considerations into energy planning. Because of this, sustainable development needs a special kind of fuel such as hydrogen, which is sustainably and economically available at reasonable cost without giving harms to the society and environment recently [3]. In this point of view, solar energy based-hydrogen production techniques are seemed to be more simple and convenient than other methods because of the sustainability and availability of the solar energy. In literature, most used solar hydrogen production methods are mentioned as photovoltaic, photoelectrolysis, photobiolysis, solar thermal energy, and solar thermochemical energy. Bilgen [4] studied on photovoltaic electrolyser systems and reported the system performance as 10.33%. Kelly and Gibson [5] made comparisons due to the types photoelectrochemical devices and found their efficiencies as 5–6%. Akkerman [6] examined the types of photobioreactors and photosynthetic efficiency depending on solar energy which was about 10%. Sturzenegger and Nuesch studied with Mn_2O_3/MnO reaction which is one of the metal oxide cycle and calculated efficiencies of 26–51% when ignoring separation steps, and 16–21% while taking all steps [7]. On the other hand, Midilli and Dincer [3] derived important sustainability and environmental impact parameters. They reported that the exergetic efficiency of the pem fuel cell was 0.55 while the sustainability and environmental benign indexes were 1.68 and 2.0335, respectively. Indeed, the environmental destruction index was found as 0.428 [3].

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Also, Rosen and Dincer [8] studied on sustainability of power plants. In this paper, environmental and sustainability aspects have been studied for an electrolyser using exergy analysis method because there are not so many studies when the literature has been surveyed. Using these parameters, systems or equipments can be classified easily due to their advantages and disadvantages objectively in the point view of sustainability & environmental parameters and exergetic efficiencies. For example, a system can be exergetic, sustainable and environmentally benign while other system/equipment can not be. These parameters reveal the important points of the whole system; applications with higher exergetic sustainability potential and lower environmental destruction index should be used. This is the main motivation behind the present study.

2. Solar hydrogen production methods

Solar hydrogen production techniques can be generally defined in five different ways as follows: (i) solar thermal energy, (ii) photovoltaic energy, (iii) photoelectrolysis, (iv) photobiolysis, and (v) solar thermochemical. Here, photovoltaic, photoelectrolysis and biophotolysis can be classified as low temperature applications while solar thermolysis, solar thermochemical cycles are high temperature applications [9]. The electricity generated from solar energy via appropriate power generating technologies can be used to produce hydrogen by electrolysis technique. Solar hydrogen production methods are shown in Fig. 1, which is compiled from the literature [10,11].

2.1. Hydrogen production by solar-thermal energy

Hydrogen can be generated directly via thermal decomposition of water; called as thermolysis; which occurs at extremely high temperature in a solar reactor [12,13]. The single step reaction can be written as follows:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (1)$$

In solar water thermolysis, water can be split into hydrogen and oxygen molecules under reduced pressure, at above 2500 K [14]. As seen in Fig. 2, decomposition of the water needs high temperature heat sources for having a suitable degree of dispersion and the energy requirement of the reaction can be supplied from the sun using concentrated solar systems, which direct the solar radiation to the heliostat of the reactor. In applications, the maximum available reaction temperature is limited likely 2500 K because materials of the membranes used in the process can not withstand to the thermal shocks occurred by high flux solar radiation [14,15].

Therefore, it is thought that direct solar water thermolysis will have a little economical and technological lifetime in the future. Kogan [15] undertaken a parametric study about the variables affecting direct solar water thermolysis and proved that as the reactor temperature increased from 2000 K to 2800 K, the maximum hydrogen yield increased [15]. On the other hand, hydrogen can be indirectly produced by electricity generation. For indirect hydrogen production, the electricity used in the electrolysis reaction is generated by solar thermal power plants, which work due to the thermodynamic cycles such as Rankine, Stirling or Brayton [16]. Steinfield [17] studied about a solar thermal plant, using heliostat field and solar tower system generated 10 MW electricity and had a total yield of 21.7% [17].

2.2. Photovoltaic panel-based hydrogen production

Photovoltaic panels based hydrogen production systems have been applied since 1980s [18]. Hydrogen can be produced by electrolysis of water and the energy necessary for the reaction can be supplied from the electricity, generated by photovoltaic panels.

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \quad (2)$$

The photovoltaic systems, which have to produce stationary energy, can be examined in two main groups generally [19]: (i) Grid- tied systems are designed to prevent the problems about the continuous working of the electrolyzing process by combining the photovoltaic panels with an input from the grid. (ii) Stand- alone systems are required when the photovoltaic based systems are applied far away from the grid. For hydrogen production, a typical stand alone system includes photovoltaic panels, a charge controller, storage batteries, a DC–DC converter and an electrolyser which can be seen in Fig. 3 [5]. One of the advantages of this system is evaluating problems about unbalanced charges and grid connections [20]. Lehman [18] studied about Schatz solar energy project which was a photovoltaic electric power plant using hydrogen as the energy storage and a PEM fuel cell as the regeneration technology. The overall electrolyser efficiency of the plant was found as 76.7% while the pv efficiency was 8.1%, and a hydrogen production efficiency of 6.2% [18]. Although the costs of the pv systems are high, there is an inclining interest in the usage of these

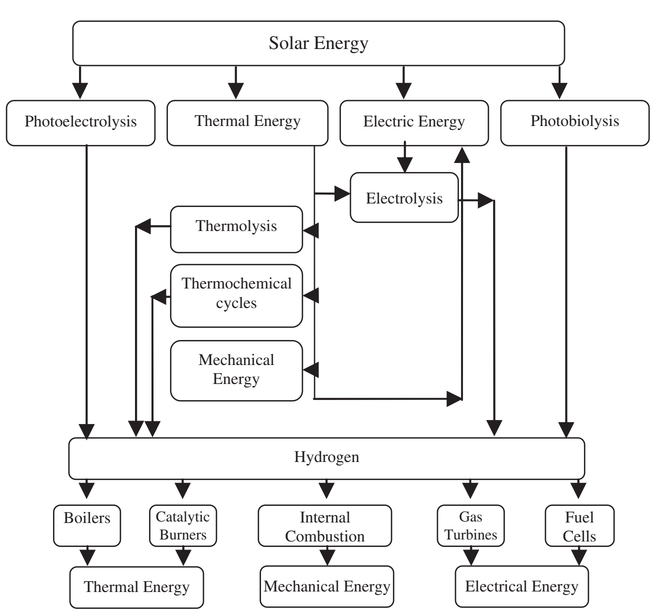

Fig. 1. Solar hydrogen energy production and utilization methods [10,11].

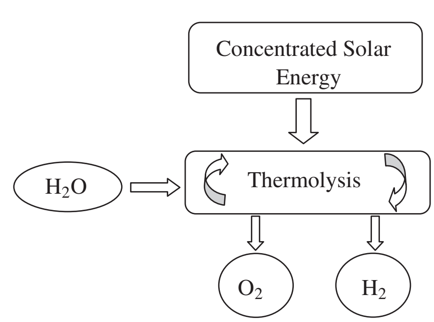

Fig. 2. Solar thermal hydrogen production methods.