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REVIEW ARTICLE

Hydrogen Production by Artificial Leaf and Influence of Artificial Leaf on Renewable Energy

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HIGHLIGHTS

- In this study, electric production with artificial leaf, which is one of the alternative energy production methods, was examined.
- Another result of this study, the effects of artificial leaf on renewable energy are explained.
- This study suggests that we should turn to alternative energy sources in the future due to the fact that conventional energy sources we use today are limited.

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ABSTRACT

With the ongoing oil crises, rapid declines in non-renewable sources, emerging greenhouse gases, energy consumption, and increasing in CO2 release are increasing the importance of renewable energy. For these reasons, artificial leaf technology has been developed to both increase alternative energy production and reduce CO2 emissions. With the widespread use of new sources, it is anticipated that greenhouse gas emissions can be reduced. One of the newly discovered sources is artificial leaf technology. Hydrogen is an element found on earth in the form of oxygen compounds (H2O). With this technology, water molecules are H2 produced by hydrolyzing water in a manner similar to photosynthesis in plants. With this technology, the water components, hydrogen and oxygen, are separated from each other by the help of light and converted into energy sources. Photosynthesis reaction of artificial leaf is much more effective than real leaf. The effect of the artificial solar leaf believe they can improve even more in the future. In this study, the importance of artificial leaf technology in terms of renewable energy sources and working principle are examined. In addition, the effects of this technology on energy production were investigated.

Contents

1. Introduction

Non-renewable energy sources (coal, oil, natural gas, etc.) we are using today are expected to be the most important consumed energy sources for the next 30-40 years [1]. Unfortunately, these resources are at risk of exhaustion after a certain period of inability to be unlimited. This depletion is pushing scientists into new quests. Energy resources are divided into three groups, which are; (i) fossil energy (ii) nuclear energy, and (iii) renewable energy [2].

Many factors, such as oil crises, emerging environmental disasters, the long time required for formation of new fossil resources, and the risk of radiation caused by the use of nuclear energy accelerate the search for new and renewable

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energy sources and harvesting technologies [3]. Not having the risk of depletion and being renewable in short periods of time, or rather being infinite, has increased the interest in renewable energy. The policies, incentive systems and procurement guarantees imposed by the states are effective in making large investments in renewable energies [4]. When we look at the renewable energy sources used in the world today, the most used ones are; Hydraulics, wind, geothermal, biogas, tidal and solar energy.

Although the types of sources are different, basically they are all used to meet the increased demand for energy. Hydrogen energy is one of the most widespread among these sources today [5]. These renewable energy sources and modes of use are shown in Table 1.

Table 1 Energy sources and usage patterns [6]

Energy Resources	Energy Conversion and Usage
Hydraulic	Electricity Generation
Biogas	Heat and Power Generation, Gasification
Geothermal	Heating, Hydrothermal, Electricity Generation
Solar	House Systems, Collector Hot Water
Direct Solar	Photovoltaic, Thermal Solar Power Generation
Wind	Wind turbine
Wave (tide)	Wave Current

Table 2 Change of renewable energy sources by years [2]

	2001	2010	2020	2030	2040
Total Consumption (million tons of oil equivalent)	10,038	10,549	11,425	12,352	13,31
Biogas	1080	1313	1791	2483	3271
Large Hydraulic	22.7	266	309	341	358
Geothermal	43.2	86	186	333	493
Small Hydraulic	9.5	19	49	106	189
Wind	4.7	44	266	542	688
Solar Energy Thermic	4.1	15	66	244	480
Photovoltaic	0.1	2	24	221	784
Thermal Photovoltaic	0.1	0.4	3	16	68
Sea (Tide, Wave)	0.05	0.1	0.4	3	20
Total Renewable Energy	1,365.5	1,745.5	2,964.4	4289	6351
Contribution of Renewable Energy Source (%)	13.6	16.6	23.6	34.7	47.7

The amount of energy used today is an indicator of the level of development of the countries. Along with population increase, the energy consumed is rapidly increasing. Countries having 25% of the world's population have 75% of the world's energy consumption. In this respect, investments in renewable energy sources are higher in developed and developing countries [7]. With the increasing investments at the beginning of the 2000s, major changes in renewable energies come to the fore. Table 2 shows the estimated ratios of renewable energy sources in the years 2020, 2030 and 2040, and the ratios of total energy consumption, based on the usage rates of renewable energy sources in 2001 and 2010.

Solar energy opens up different ways of energy production with new technologies emerging day by day. Reliability of the source and high potential is effective in the development of the solar energy technologies and applications. In recent years, it has become more common to convert it into electricity with photovoltaic technology, which is used in hot water, steam and drying processes [8].

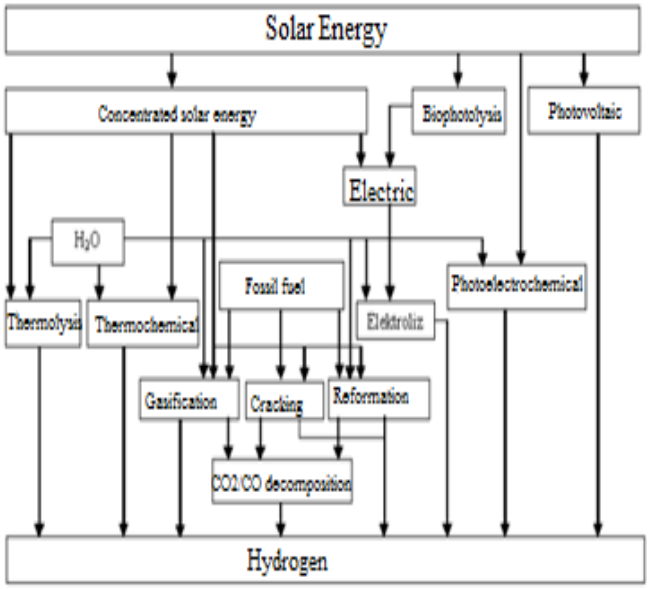


Figure 1 Obtaining hydrogen energy with solar energy [9]

There are various methods of generating electricity from solar energy. The conversion of solar energy into electrical energy in a clean and non-hazardously was carried out with solar panels made of silicon semiconductor. While there are various methods in the production of electrical energy, various problems occur in the storage of this energy. One of the ways to eliminate these problems is the hydrogen storage method. In addition, the energy stored by H2 resulting from electrolysis can be used completely [9]. Basically, methods of obtaining hydrogen from solar energy are; (i) photovoltaic (PV), (ii) photoelectrochemical, (iii) photobiological, (iv) solar thermal energy and (v) solar energy [10]. The scheme for obtaining hydrogen with solar energy is shown in Figure 1.

2. Artificial Solar Leaf

2.1. The Working Principle of Artificial Leaf

The working principle of artificial leaf is similar to that of photosynthesis in plants. Photosynthesis; a phenomenon in which water and minerals that plants receive through their roots enter a chemical reaction with the help of sunlight [11–13]. Water molecules are separated into hydrogen and

oxygen by the effect of sunlight. Figure 2 shows the photosynthesis phenomenon caused by the effect of sunlight.

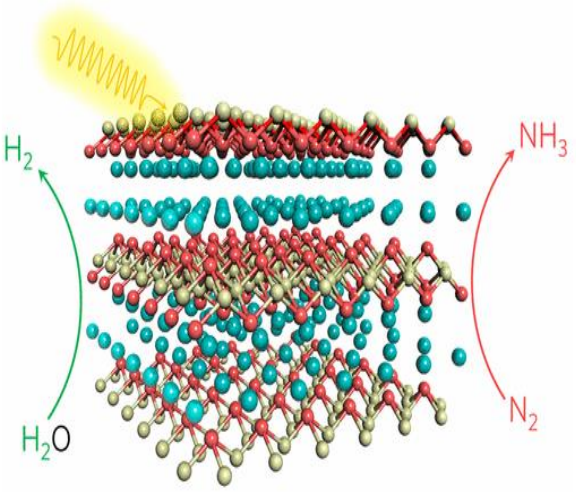


Figure 2 Photosynthesis from sunlight [10]

Breaking down of water into hydrogen and oxygen with the help of sunlight; yields a potential clean, sustainable and abundant energy source (Figure 3) [14, 15]. This is a common occurrence in plants we encounter in our daily lives.

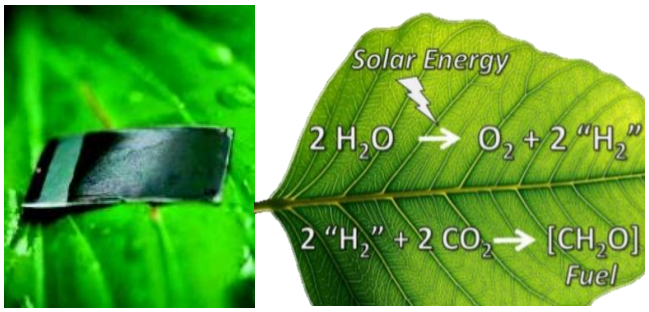


Figure 3 Artificial Solar Leaf [16, 17]

Its characteristic size represents the average impact length across the airflow and has been calculated by the following equation;

$$d = \left(\frac{\int_0^1 w(y)dy}{\int_0^1 w(y)^{0.5}dy}\right)^2 \quad (1)$$

Here, d (cm) is expressed as the characteristic size. In addition, w (y) is the width of the leaf, and there is air flow between the base of the leaf and the leading edge of the artificial leaf. This leaf is made by combining a pair of glossy brass layers with a thickness of 0.1 mm. The micro-heater, which is 0.1 mm in diameter, is obtained by electrically insulated with enamel coating and tightly compressed with double-sided tape for full heat transmission to brass plates. These leaves are ensured to be heated with energy from a power source to the micro-heater. It is fixed to the surface of each leaf with a pair of copper thermocouples, 0.1 mm in diameter.

When extreme cases occur, the boundary layer thickness may exceed 1 cm. However, this thickness is generally at a very smaller value. Lastly, the air temperature reference of the thermocouples was located on the outside of the leaf layer. The reason they are connected in parallel is that these two pairs of thermocouples are meant to detect the average leaf–air-temperature difference on the two surfaces [18]. Figure 4 shows the schematic diagram of an artificial leaf.

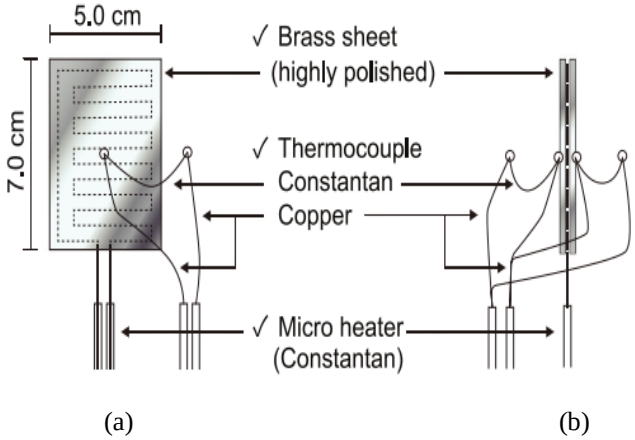


Figure 4 Schematic diagrams of an artificial leaf for evaluating leaf-boundary layer conductance: side (a) and front (b) views [18]

The synthetic leaves that are artificially produced, such as the photosynthesis phenomenon that occurs in the plants, are produced by breaking down water into its components under light energy and thus producing hydrogen and oxygen. This leaf produced has a solar cell which is made cheaply with both catalytic materials of silicon on both surfaces. No electrical connection is required for operation [19].

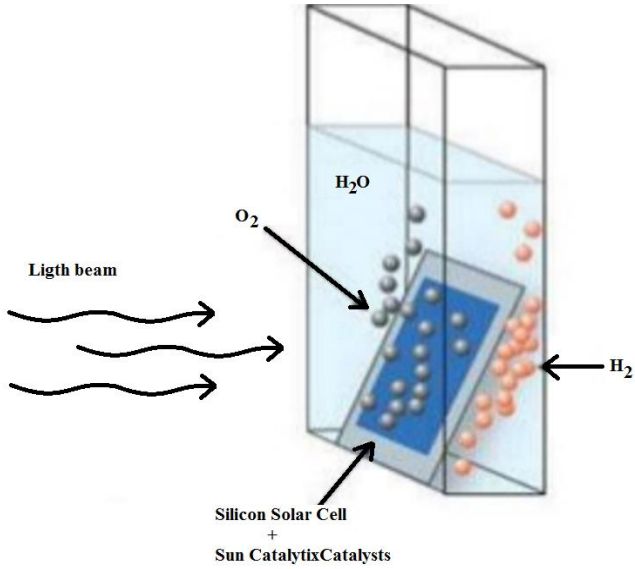
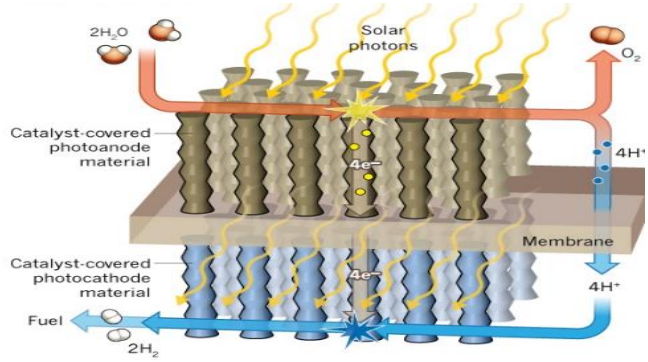
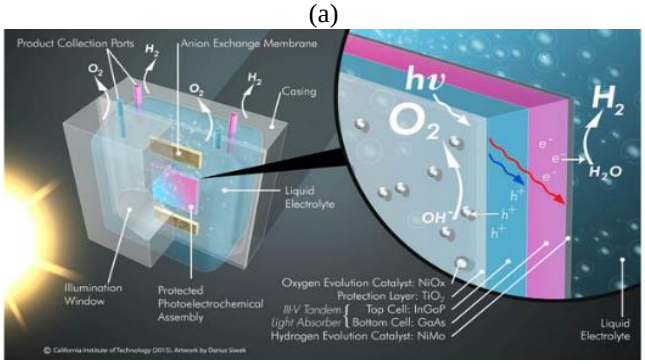


Figure 5 Structure of Artificial Solar Leaf [20]

The water droplets on the leaf are broken down into their constituents by the effect of light by the help of the electrodes placed on both sides of the artificial leaf laid in a container. When artificially obtained leaf surfaces are placed in such a way that they are not influenced by one another, the dissociating water molecules provide hydrogen molecules on one side and oxygen molecules on the other side (Figure 5) [21]. Figure 6 shows the separation of water molecules by the light effect of the leaf.



(a)



(b)

Figure 6 Water molecules dissociated by light (a) [22] (b) [23]

Under normal conditions, breaking down hydrogen molecules requires a very high cost. In this respect, the cost of the hydrogen obtained by normal means is more expensive than the resulting product. Instead of such a system, artificial leaves developed with solar energy provide less costly hydrogen molecules from water molecules. Therefore, the development of such methods is important in terms of diversification of energy resources and in reducing the ratio of CO_2 in the atmosphere[24]. At present, the cost for obtaining hydrogen is the cost of a solar panel and the cost of hydrogen from electrolysis panel is $7. This is only 1-2 dollars costly than fossil resources. With the newly developed artificial leaf, it costs as low as $6.50 [17]. It is not predicted that the cost will be too low, but it could be reduced in parallel with newly developed semiconductor technologies.

3. Conclusions

With the ever increasing population and the capability of creating a solution to the energy demand, clean energy is gaining great importance along with newly developed technologies. Using these sources, the newly developed artificial sunscreen converts water molecules into fuels, such as hydrogen and oxygen, by breaking it down with only light effect, without any carbon emission. Artificial photosynthesis is also seen as a system developed to reduce the increasing CO_2 concentrations in the atmosphere, and to prevent new CO_2 emissions by using Sunscreen technology.

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