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Green Hydrogen Production - The Energy of the Future

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Abstract

Hydrogen is the most efficient energy carrier. It can be obtained from many sources like fossil fuels and water. Most of the energy generation uses fossil fuels, resulting in environmentally unhealthy activities and the production of toxic by-products, which contribute to environmental degradation and climate change. Among many hydrogen production methods, non-polluting and high purity of hydrogen can be obtained by water electrolysis. The produced hydrogen and oxygen can be directly used for fuel cell and industrial applications. Overall water splitting results in only 4% of global industrial hydrogen being produced by electrolysis of water mainly because of economic problems. Nowadays, the increase in demand for green hydrogen has increased the interest in PEM water electrolysis. In this work, we look at various methods of hydrogen production, namely water electrolysis and solar water splitting. This project also briefly describes the applications of green hydrogen along with its effectiveness to replace the current method of hydrogen production.

Keywords: Hydrogen fuel cell, green energy, solar water splitting, water electrolysis

1. Introduction

The rising concern about climate change coupled with the exhaustion of fossil fuels and energy security are major challenges worldwide. Economic growth in the last few decades has been strongly dependent on fossil fuels as sources of energy. These resources are limited in the long run and there are environmental concerns that have led to increased research in the field of clean energy. Solar Energy could act as an effective source that addresses our energy needs while also considering the environmental problems faced by mankind.[2] Reactions driven by solar energy generally occur under milder conditions, allowing higher selectivity for reactions. The energy in the future should ideally be based on renewable energy and nuclear as clean energy, despite the serious consequences in case of an explosion in a nuclear power plant. The exploitation of the huge energy potential of solar radiation and its effective conversion to chemical

energy carriers such as hydrogen is a subject of primary technological interest. The advantage of solar energy is known to everyone. It is an available, non-depletable, and non-polluting source that is the most abundant form of energy available to mankind.[3]

Presently, A large percentage of hydrogen available is produced by natural gas reforming. An increase in usage of clean and renewable sources has resulted in the improvement of electrolysis processes and interesting methods for the production of these new sustainable energies.[1]

Because of its excess, less value, and the lack of CO_2 emissions during its dissociation (water splitting) to hydrogen and oxygen, water is the ideal raw material for hydrogen production.[4]

Hydrogen is regarded as a highly effective energy replacement for fossil fuels and, in the impending future, offers many advantages. Hydrogen can generate close to 39.4 $kWh.kg^{-1}$ during its combustion, which is three folds more than any other fuel. The main advantage of hydrogen is that it only releases water in the combustion process and it can be used in most places where fossil fuels are currently used.

Hydrogen can be stored for a long period with minimal losses and can provide electricity when needed. This can be of great use for an efficient operation of electricity production from discontinuous sources as in the case of renewable energies with respect to this, the surplus electricity produced can be used to produce hydrogen and then stored to meet the demand during peak hours.

The hydrogen produced from solar energy would be transported or stored and burned as energy is needed to be transported or stored and burned as energy is needed. Hydrogen can be used as fuel for electric vehicles, which enhance the sustainability of the transport sector, which accounts for almost 25% of the world GHG emissions.[5] Hydrogen can also be used as raw material for many other industrial applications, for example, ammonia production, soil enrichment, production of methanol, metal refining among others. This phenomenon which has become popular in recent times, is called as "Hydrogen Economy".6

2. Methods of Production

2.1 Hydrogen production by water electrolysis

Water electrolysis is an electrochemical process in which electrical energy is the driving force of chemical reactions. It is considered a well-known principle to produce oxygen and hydrogen gas.[7] Although the discovery of electrolysis of water was first observed in acidic water, an alkaline medium is preferred in industrial plants since corrosion is easily controlled and relatively cheaper construction materials are used. The use of wind and solar energy, being a green and simple process, is a sustainable method of hydrogen production by water electrolysis due to its high purity.[8]

2.1.1 Alkaline Electrolysis

In this process, two molecules of water are reduced to one molecule of hydrogen and two hydroxyl ions at the cathode. In today's time, alkaline electrolysers (AE) are dominant for large-scale hydrogen production since it is economically favourable, more accessible, and economically feasible. The most commonly used electrolyte for AE is the solution of potassium hydroxide (KOH) in water. This has a high degree of hydrogen ion concentration in the electrolyte with a pH of 13 to 14. Their concentrations range from 20% to 30%, while their energy utilization ranges from 60% to 90%. Advanced AEs operate at a relatively low voltage of 1.6V as compared to conventional AEs, which operate at a voltage of 1.8V to 2.2V. All in all, AEs can produce hydrogen at a rate of $10m^3h^{-1}$, with larger AEs achieving between $10m^3h^{-1}$ to $100m^3h^{-1}$.[9] After the process, hydrogen leaves from the surface of the cathode recombined in a gaseous form, whereas the hydroxyl ions transfer under the influence of the electrical field between the cathode and anode through a porous diaphragm.[7] This entire process is demonstrated in figure 1 below, which shows the working mechanism of alkaline water electrolysis.[10]

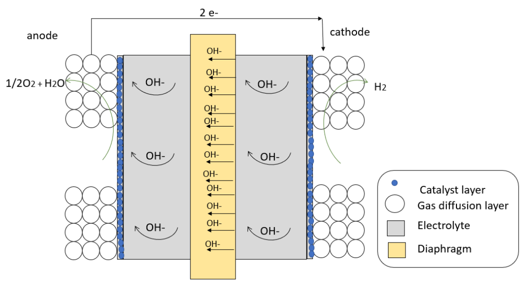

Fig 1. Alkaline Water electrolysis

2.1.2 Proton exchange membrane (PEM) water electrolysis

This method is based on the use of a polymeric proton exchange membrane as a solid electrolyte. In terms of sustainability and environmental impact, PEM is a favourable method for converting renewable energy to pure hydrogen. The electrocatalysts for PEM electrolysis are noble metals like Pt/Pd for hydrogen evolution at the cathode and IrO_2/RuO_2 for oxygen evolution at the anode. The use of these expensive noble metals makes it more costly than alkaline electrolysis. PEM water electrolysis is followed by the pumping of water to the anode, where it is split into oxygen, protons, and electrons.[11] The protons reach the cathode side through a proton-conducting medium, whereas the electrons leave the anode through an external power circuit. The standard membrane material like Nafion 117 conducts the hydrated protons from the anode side to the cathode side. Finally, at the cathode side, the protons and electrons recombine to produce hydrogen. This technology was developed much later as compared to alkaline electrolysis and has the following advantages over alkaline electrolysis:

1. More reliability and greater safety due to absence of a caustic electrolyte
2. Some materials could sustain higher differential pressure without much damage
3. Lower gas permeability
4. High proton conductivity

2.1.3 Steam electrolysis

The major advantage of this method is that it reaches a higher total energy efficiency as compared to the other two methods due to lesser high electricity consumption. In conventional steam electrolysers, a mixture of steam and hydrogen is supplied to the cathode side, where water is decomposed. On the anode side, usually, air is supplied.[12] However, this used a lot (about 60% to 70%) of the total electrical power. Due to this, a newer approach has been developed to lower the electricity consumption by using natural gas in order to reduce chemical potential difference across the electrolyser cell. In this case, the air in the anode is replaced by natural gas, causing the lowering of the open-circuit voltage and, in turn, the electricity consumption.[13]

Various research and development trends suggest that mankind would grow to become a so-called hydrogen economy. Keeping in mind a growing population and better lifestyle, water electrolysis can potentially be a very important process for producing hydrogen.[14]

2.2 Solar Water Splitting

This refers to any process in which solar energy is used to produce hydrogen from water without going through intermediate electrolysis steps.

2.2.1 Photo-electro chemical water splitting

Semiconductor-based PEC water splitting is one of the most promising methods of producing “GREEN HYDROGEN.” There are many challenges to commercialization of this method.[15] The oxidation and reduction reaction takes place in their respective half cells.[16]

$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O$

(1)

$4H^+ + 4e^- \leftrightarrow 2H_2$

(2)

$2H_2O \rightarrow 2H_2 + O_2$

(3)

When designing a PEC system for water splitting, the absorption of light must generate more than the required potential difference to drive the reaction forward.[17]

When designing a system that converts solar energy into chemical energy, we consider these specific criteria- absorptivity of the system must align with the incident solar spectrum, efficiency, and yield of photogenerated charge separation, and the chemical potentials of the separated charges. Fig 2 gives a pictorial representation of photo-electrochemical water splitting process.[18]

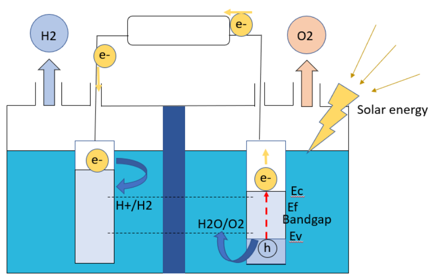

Fig 2: PEC water splitting

PEC system for water splitting consists of at least two electrodes that are separated by an ion-permeable membrane and the oxidation and reduction reactions occurring in separate compartments.[19]

While PEC-driven water splitting has been demonstrated on a laboratory scale, commercially viable systems that meet economic requirements with respect to energy and cost efficiency have not been shown till now.[20] Development of earth-abundant semiconductors is highly important for high efficiency and sustainable PEC water splitting.[21]

2.2.2 Photobiological

Photosynthetic bacteria carry out anoxygenic photosynthesis using organic compounds and reduced sulphur compounds as electron donors, which are categorized as non-sulphur and sulphur photosynthetic bacteria, respectively. Some non-sulphur photosynthetic bacteria are potent hydrogen producers utilizing organic acids, for example, lactic acid, succinic and butyric acids, or alcohols. From a practical point of view, photosynthetic bacteria are important since they can be used for dual purposes of wastewater treatment and hydrogen production.[22] Lactic acid is an excellent substrate for hydrogen production by photosynthetic bacteria, with a maximum hydrogen yield of 8 mol/mol starch-glucose from algal biomass was observed. [23]

(photoautotrophic H_2 production) Microalgae and cyanobacteria are able to use sunlight to metabolize carbon dioxide (CO_2) inside energy-rich organic compounds [$C_n(H_2O)_n$], with water (H_2O) as an additional substrate.[24]

Under anaerobic conditions, microalgae can produce hydrogen by means of water photolysis, where light is used as the energy source. The catalyst is a hydrogenase which is an enzyme that is extremely sensitive to oxygen and produced as a by-product of photosynthesis.[25]

2.2.3 High-Temperature Thermochemical Cycles

Two-step reaction cycles are naturally the simplest multistep thermochemical water-splitting methods and may be classified into one of the following three types of reactions.[26]

-Oxide type

$XO \rightarrow X + 0.5O_2$
(4)

$X + H_2O \rightarrow XO + H_2$
(5)

-Hydride type

$XH_2 \rightarrow X + H_2$
(6)

$X + H_2O \rightarrow XH_2 + 0.5O_2$
(7)

-Hydroxide type

$2XOH \rightarrow 2X + H_2O + 0.5O_2$
(8)

$2X + 2H_2O \rightarrow 2XOH + H_2$
(9)

There is two-step thermochemical water splitting by a metal oxide redox pair, the first type of cycle is called the “metal oxide process.” Redox pair of Fe_3O_4/FeO is used.

$Fe_3O_4 \rightarrow 3FeO + 0.5O_2$
(10)

$H_2 + 3FeO \rightarrow Fe_3O_4 + H_2$
(11)

The first high-temperature thermal reduction of Fe_3O_4 is highly endothermic (ΔH°298K) 319.5 $kJmol^{-1}$), and the second low-temperature hydrolysis by FeO is slightly exothermic (ΔH°298K) -33.6 $kJmol^{-1}$).[27] The two-step process eliminates the need for high-temperature H_2/O_2 separation. Two-step water-splitting cycles by an iron-based oxide (or ferrite) redox pair were developed as early as 1977 based on this thermodynamic principle and are frequently called “iron oxide processes” or “ferrite processes.”

Primarily, two or three-step cycles are preferred because of their ease of implementation, which implies favourable economics. These cycles involve few reactions and separations, therefore allaying the inaccuracies related to heat transfer and product separation. They also involve available and safe materials and a heat input temperature compatible with solar thermal energy.

The photo-electrochemical and photobiological processes are the ones that should be evolved in order to meet the energy requirements. Nowadays, systems are less than 1 percent efficient (solar to hydrogen), and they need to reach much higher efficiencies to be economical. There are no large-scale installations of either technology. The high-temperature thermochemical cycles can achieve significant efficiencies of more than 40 percent under the condition that they must use concentrated solar receivers or reactors which of reaching temperatures of more than 800º C. [28]

3 Application of Green Hydrogen

3.1 Storage

One application of hydrogen is its utilisation as a storage medium. The increased availability and dropping price of both modular decentralised electrolysers and centralised large-scale electrolysers means green hydrogen is, in some cases, already a feasible energy storage solution.

Hydrogen storage has many advantages over storing electricity in batteries. Uniquely for mid-to-long-term storage solutions, the advantages include low cost of storage capacity and the fact that the stored energy does not discharge over time.[29] This must be balanced with the fact that hydrogen may require compression for space-efficient storage. In stationary applications, metal hydride hydrogen storages could also provide a safe, mild pressure and condensed solution once costs are reduced a bit further. For transport, it is more efficient to store hydrogen in the most compact forms possible.[30] Green hydrogen storage opens doors whether it's for short or long-term storage of renewable energy for power producers to retain the value of curtailed energy when power prices become low, for extremely high shaving, or for devising green hydrogen stock that can be transported or stockpiled for any fuel, industrial or chemical uses.

3.2. Hydrogen Fuel Cell

Since hydrogen can be generated by a wide range of methods, as discussed above, it has the potential to become an energy centre in the future. The major advantage of hydrogen over electricity is that it can be stored for the long term. The basic concept of a hydrogen fuel cell is to use the chemical energy of hydrogen to produce electricity, water, and heat by the combination of hydrogen and oxygen atoms.[31] The fuel cell in general consists of three main components: a cathode, an anode, and an electrolyte. Hydrogen fuel can supply power for liquid-propelled rockets, vehicles, fuel cells, etc. Figure 3, as shown below, gives an idea of the functioning of hydrogen fuel cells in which air and fuel are mixed and unused gases and excess fuel are removed from the bottom of the fuel cell.[32]

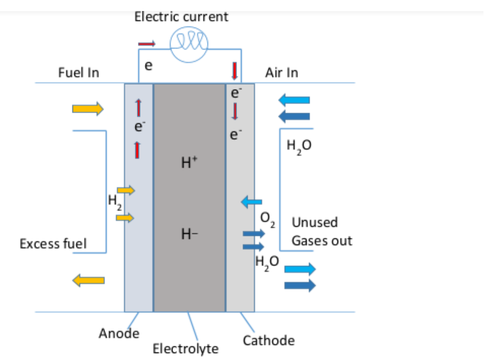

Fig 3: Hydrogen Fuel Cells

Fuel cells, where hydrogen is directly converted into electrical energy, are the most likely source of renewable energy for the future due to higher efficiency, less noise, and limited movement in parts. However, one of the major drawbacks is its low ignition energy and high energy of combustion. The basic concept of working of a fuel cell is like a battery that does not need charging if a constant source of fuel is supplied. Hydrogen is supplied at the anode, whereas air is fed to the cathode. A catalyst at the anode splits the hydrogen molecules into protons and electrons. The electrons create a flow of electricity, and the protons migrate to the cathode. They combine with oxygen to produce water and heat.

5. Conclusion

The two major methods of production of hydrogen are hydrogen production by water electrolysis and solar water splitting. These two processes use solar energy, making them green and sustainable methods for hydrogen production. The presence of hydrogen energy storage allows renewable energy to be obtained at busy generation times and to be used at low points of generation. Various applications of this green hydrogen are also discussed in detail. The feasible integration of hydrogen energy depositary with sustainable energy sources offers the prospect of economically energy-saving remote power systems and cutting in the external price of energy associated with many fossil fuels. After a few decades, hydrogen green energy is likely to be used in everyday life, and a lot of conventional and non-sustainable methods will be replaced by hydrogen energy technologies. The economics of these green hydrogen technologies will be improved as they are used more widely in different areas and applications due to their several advantages like 100% sustainability, easy storage, and low pollution. Despite the multiple upsides, one must also look at certain roadblocks to a green hydrogen energy future like large-scale hydrogen manufacturing cost, configuration investments, bulk storage, and welfare considerations. If these hurdles can be subdued in the near future, the world will have a vivid, clean, and green future using hydrogen energy.

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