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Water Electrolysis-to-Green Hydrogen: a Review of Main Extraction Methods, Storage, and its Integration with Fuel Cells

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التحليل الكهربائي للماء لإنتاج الهيدروجين الأخضر: مراجعة لطرق الاستخلاص الرئيسية، والتخزين، ودمجه مع خلايا الوقود

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الملخص:

في السنوات الأخيرة، اكتسب مصطلحا "الكيمياء الخضراء" و"مصادر الطاقة المتجددة" أهمية بالغة لدى العلماء والباحثين، لما لهما من تطبيقات واعدة في الحد من التلوث البيئي والاحتباس الحراري، الذي أدى إلى تغيرات مناخية حادة باتت تشكل تهديدًا حقيقيًا للتوازن البيئي على سطح كوكب الأرض. وقد دفع هذا العديد من الدول، كالولايات المتحدة واليابان وألمانيا والمملكة العربية السعودية ومصر وغيرها، إلى حثّ العلماء والباحثين على توظيف مصادر الطاقة المتجددة وتحويلها من مجرد حلم بيئي إلى واقع ملموس، بجعلها بديلاً للوقود الأحفوري الذي لا يمكن تصور التقدم التكنولوجي بدونه.
ومن أهم تطبيقات الكيمياء الخضراء إنتاج ما يُعرف بالهيدروجين الأخضر (مصدر طاقة متجدد)، الذي يُوصف بأنه وقود المستقبل، كونه بديلاً ممتازًا للوقود الأحفوري، ما يتيح استخدامه في تطبيقات لا حصر لها دون أي انبعاثات غازات ملوثة.

الكلمات الدالة: الكيمياء الخضراء، الهيدروجين الأخضر، خلية الوقود، الطاقة المتجددة، الوقود الأحفوري، الاحتباس الحراري، غازات الدفيئة **(GHG).**

Abstract

In recent years, the terms green chemistry and renewable energy sources have become important terms that scientists and researchers keep talking about and about their promising applications in reducing environmental pollution and global warming, which led to sharp changes in the climate and thus became a real threat to the vital balance on the surface of the planet. This led to the racing of many countries such as the United States, Japan, Germany, Saudi Arabia, Egypt, and others countries in urging the efforts of scientists and researchers towards applying renewable energy sources and converting them from a green dream into a tangible reality by making them an alternative to fossil fuels, which technological progress cannot be imagined without its presence.

One of the essential applications of green chemistry is the production of what is called Green hydrogen (renewable energy source), which is described as the fuel of the future, by making it an excellent alternative to fossil fuels, and thus its entry into countless applications without any emission of any polluting gases.
This article aims to shed light on green hydrogen in terms of its concept, extraction methods, and how to store it and discuss the pros and cons of it and its integration with fuel cells.

Keywords: green chemistry, green hydrogen, fuel cell, renewable energy, fossil fuels, global warming, greenhouse gases (GHG).

Introduction

Since the first industrial revolution that appeared in the nineteenth century in England and then spread to the countries of Western Europe and from there to the rest of the world, the planet is not as it used to be, New phenomena have appeared such as a blazing dry summer and bitterly cold winter, in addition to the increase in storms, floods, and forest fires [1]. All these phenomena prompted researchers to ask what happened to our planet. Are human activities the main cause of these climate changes? Through the continuous search for the causes of these sharp changes in the climate, they found the answer to the question, that the greenhouse gases, which are symbolized by (GHG), are the main cause of these changes in the climate, and they can be defined as a group of gases that have the ability to absorb infrared radiation that is reflected by the earth and thus it reduces the heat lost from the earth and cause the temperature of the atmosphere increased, These greenhouse gases (CO_2, CH_4, O_3, and N_2O) are very important for maintaining thermal balance and thus preserving existence on the surface of our planet ,But when it exceeds its natural rate, it will cause climate disasters.[2] On the other hand, the evolving technology that has been experienced since the nineteenth century until now is also one of the main reasons that led in one way or another to an increase in the percentage of (GHG). This is evident through carbon dioxide emissions from factories, which represent about two-thirds of greenhouse gas emissions that cause global warming, as it has been observed through recent studies that the earth's temperature increased by 1.5°C than it was in 2010, and it is expected that the increase in global mean temperature will reach 3.5°C by 2100, which prompted the necessity of concluding a global agreement to reduce dangerous climate changes, which was known as the Paris Agreement, which aimed to reduce global warming to less than 2°C and enhance the ability of countries to deal with the effects of climate change and strive to reach zero carbon emissions by 2050. [3] This means that there is a real danger threatening the planet, and it has become the duty of scientists and researchers to find radical and quick solutions to restore balance to the environment by finding new sources of energy that are inexhaustible and do not affect the vital environmental balance and serve technological development at the same time instead of non-renewable energy sources and indeed scientists and researchers rushed to find effective solutions and thus appeared what is called green chemistry can be defined as a branch of chemistry, which includes the use of renewable resources and the reduction of dependence on non-renewable resources. So countries around the world have begun, albeit with somewhat slow steps, to form an alliance aimed at reaching zero emissions of CO2 by 2050. However, emissions must be reduced by about half by 2030 to maintain an acceptable rise in temperature, which is less than (1.5) °C through a decrease in fossil fuel production by approximately 6% annually during the decade 2020-2030 by using sources of alternative energy instead of fossil fuels to meet climate-neutrality targets by mid-century. [4]

It has become clear to everyone that reducing the use of fossil fuels has become inevitable due to their high prices and their direct impact on climate change due to carbon emissions and the pollution it causes as a result of these emissions, From here, the scientists turned their attention to green hydrogen as an ideal solution to the world's energy problems because it is the inexhaustible element, in addition to an important advantage, which is that when it burns, it does not produce any pollution or harmful emissions to the environment, but rather all emissions that result from its combustion are heat, pure water, and electricity. This is exactly what scientists are looking for, based on this reason, they found that it is necessary to shed Light in detail on green hydrogen in terms of its concept, extraction methods, and promising applications in the future and discuss the pros and cons of it and its integration with fuel cells.

2-1 What is Green Hydrogen?

Green hydrogen can be defined as the hydrogen that is produced by the process of electrolysis of water, depending on renewable energy, such as wind or solar energy, it is classified as environmentally friendly because when produced or consumed it does not lead to the emission of any gases polluting the environment, compare with blue hydrogen, which is prepared by using fossil fuels, which when burned leads to the emission of gases polluting the environment, green hydrogen is a colorless and odorless gas, there are several different types of *its* (black, gray, blue, pink, turquoise, and green hydrogen). A distinction is made between these types depending on the extraction method and the energy source used in their production [5, 6], Where black hydrogen is produced through the use of black coal, and this type of hydrogen is considered one of the most harmful types to the environment due to the emission of greenhouse gases into the atmosphere when burned, while gray hydrogen is produced through the use of natural gas, which is also considered harmful due to the emission of (GHG) also blue hydrogen, it is similar to gray hydrogen as well It is produced using natural gas, but it differs from gray in terms of capturing greenhouse gases and imprisoning them in the ground before they are released into the atmosphere, Pink hydrogen is generated by electrolysis powered by nuclear power. The nuclear-produced hydrogen is also known as purple hydrogen or red hydrogen. While *turquoise*, hydrogen is made using a process called pyrolysis of methane to produce hydrogen [7]. [Figure.1] illustrates a comparison of the production process for the "blue" and "green" types of hydrogen.

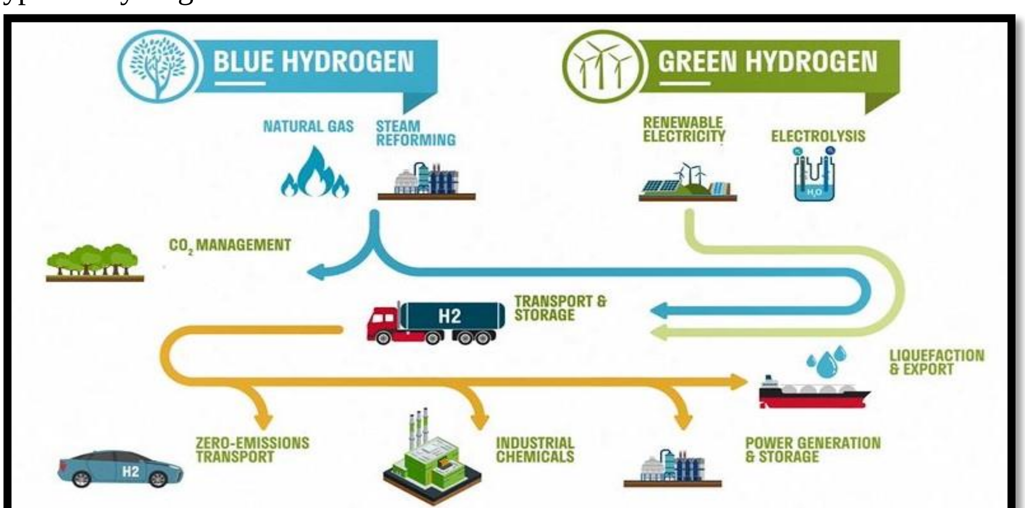

Figure.1. A comparison of the production process for the green and blue types of hydrogen. [8]

3-1 Green Hydrogen & Production Methods

Generally, hydrogen can be produced either from renewable sources such as solar and wind energy or by using non-renewable sources such as fossil fuels. However, hydrogen production in

2020 relied entirely on fossil fuels and was accompanied by the liberation of a high percentage of unwanted carbon dioxide, as the production rate reached only 0.7% of natural gas, but in 2021 a qualitative leap occurred in the percentage of production for Green hydrogen is up 20% compared to 2020, but it still represents a small part of total production [9], There are many low-emission technologies used to produce green hydrogen, and perhaps the most important of these technologies is the electrolysis of water and biomass gasification. It is worth noting that these low-emission technologies represent only about 1% of the current global production of green hydrogen, which is a very small percentage. The technologies used to produce green hydrogen are greatly affected by the cost of electricity, as the average cost of producing green hydrogen through electrolysis of water using renewable energy sources is about (6-16) times higher than the production of normal hydrogen prepared by relying on natural gas, and it is expected to reduce the cost of producing Green hydrogen by electrolysis process using solar energy and wind electricity analysis in 2030. [10]

1-3-1 Direct Water Splitting:

Solar energy is used directly to decompose water molecules into the form of oxygen and hydrogen [Figure.2], this process is also called photovoltaic water separation. The water-splitting process uses semiconductor materials to convert solar energy directly into chemical energy in the form of hydrogen. This process is characterized by the fact that it requires approximately 9 liters of water to produce Kg of green hydrogen, which is less than the amount of water needed in the electrolysis process using non-renewable energy sources, which need 12 liters of water to produce Kg of hydrogen. [11]

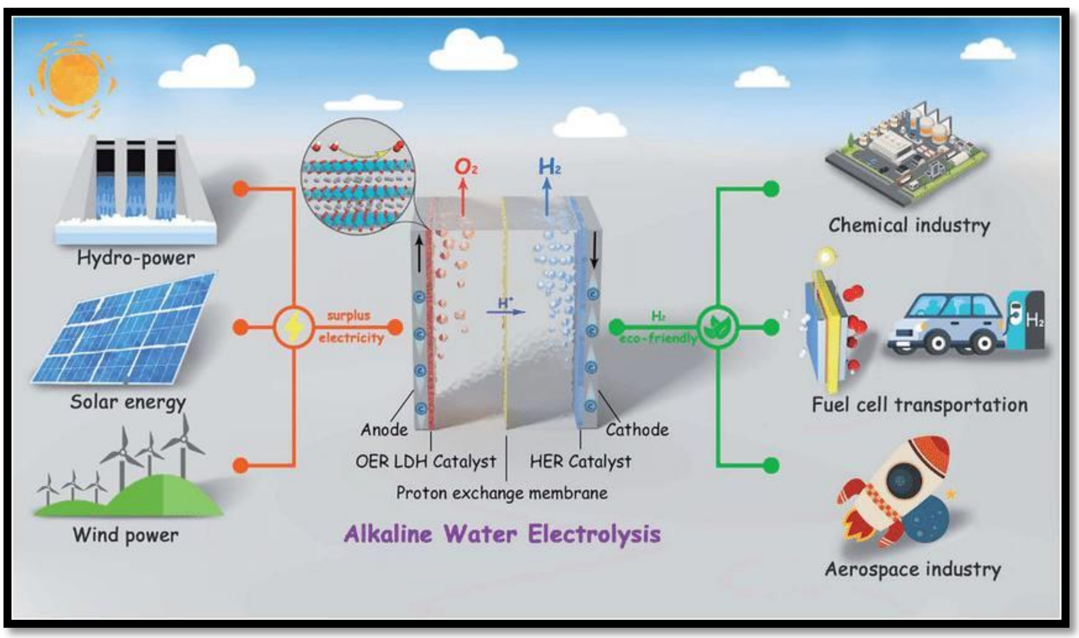

Figure.2. Photovoltaic driven water splitting to provide hydrogen environmental-friendly [12].

2-3-1 Biomass Gasification:

It is one of the technologies used to produce green hydrogen through a controlled process that includes heat, steam, and oxygen to convert biomass such as agricultural waste and wood into hydrogen and other products without combustion. This method is characterized by being cheap and its raw materials are available and simple, [Figure.3]. Since growing biomass removes CO_2 from the atmosphere, this method has a very low CO_2 emission. [13]

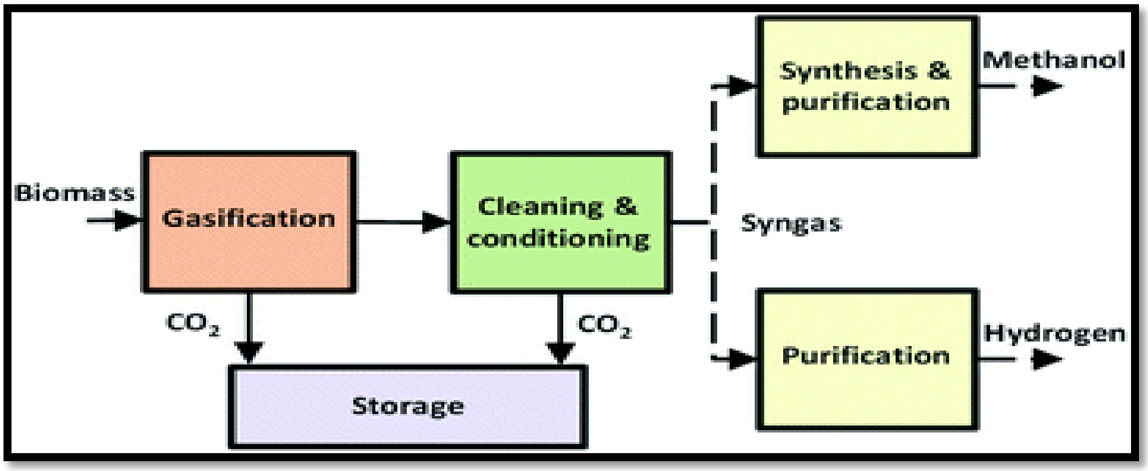

Figure.3. Green hydrogen Production from Biomass [14].

[Figure .4] below reviews the most important methods for the synthesis of hydrogen from non-renewable and renewable sources: [15]

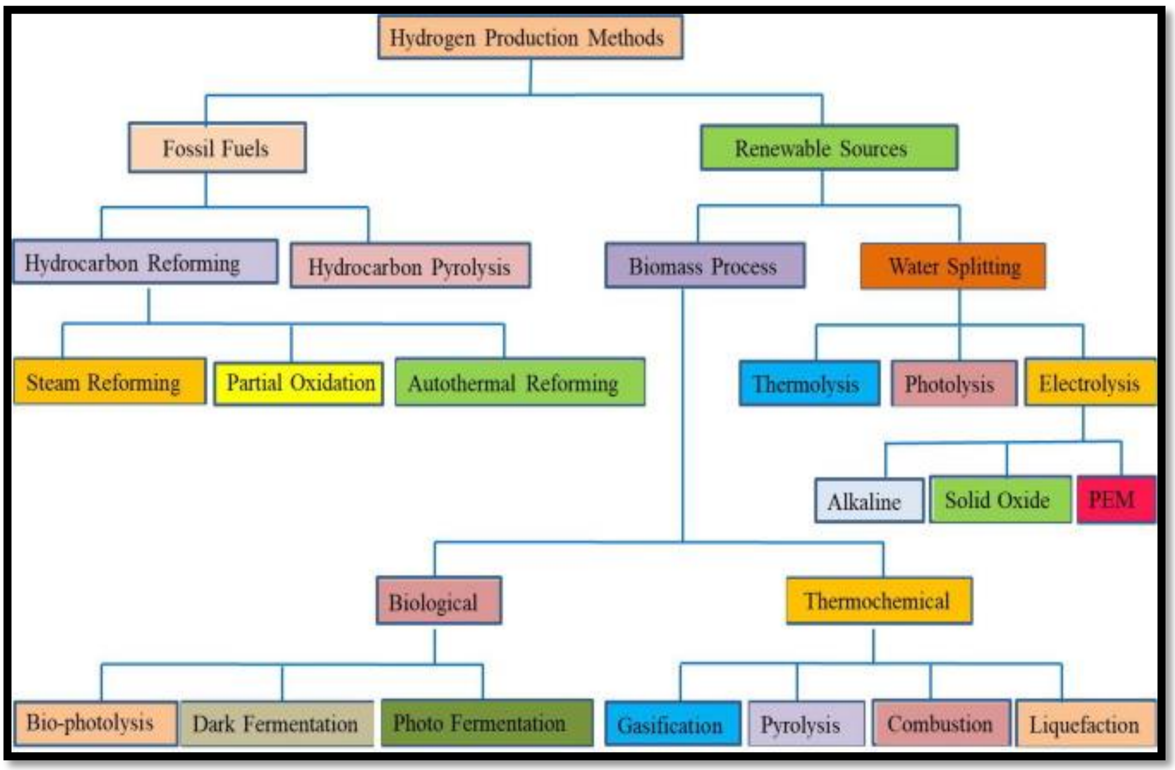

Figure .4. The most important methods for the synthesis of hydrogen from non-renewable and renewable sources.

4-1 Profits of Green Hydrogen

Green hydrogen has countless benefits, as it is almost becoming a miracle of this century because of its advantages and promising applications. The most important advantages of green hydrogen [16-19]:

1-4-1 Organism health and the environmental safety

Green hydrogen is characterized as a clean and environmentally safe fuel, due to the fact that when it burns, it does not produce any pollution or harmful emissions to the environment, rather all emissions that result from its combustion are heat, pure water, and electricity.

2-4-1 Abundance and sustainable

Hydrogen is one of the lightest and most abundant chemical elements in the universe. It is a colorless, odorless, and non-toxic gas. It is not found alone in nature but is usually associated with a number of elements to form different chemical compounds. It can be obtained from a large number of different sources, including renewable and non-renewable. Among the most important renewable sources through which green hydrogen can be produced are solar power, wind power, hydropower, and other sources. Therefore, green hydrogen is considered sustainable.

3-4-1 High potential and energy efficiency

Green hydrogen is more energy efficient when compared to fossil it contains about three times more energy than diesel fuel and natural gas. Also, we noted that green hydrogen fuel cells have a very high energy compared to regular fuel cells and have a longer life, and require less maintenance than regular fuel cells. As it is known, the large factories depend mainly on non-renewable energy, and therefore they emit a large amount of carbon dioxide gas into the atmosphere, which is considered one of the most important greenhouse gases that cause global warming. This problem can be solved by making green hydrogen replace coal because of Its high ability to generate energy without emitting any polluting gases.

4-4-1 Suitable for distant areas

Many remote areas are difficult to reach, and therefore the process of equipping these areas with non-renewable fuel sources for transportation and heating homes will be very difficult and expensive at the same time. Therefore, the use of green hydrogen as a source of renewable fuel is very suitable for these remote places.

5-4-1 Fuel Cell Vehicles

The operation of fuel-cell vehicles is one of the most important applications that are attributed to green hydrogen, as it was found that vehicles that use green hydrogen as a fuel are more efficient than vehicles that operate with electric batteries because the first requires only three minutes to be filled with green hydrogen, while electric vehicles need Equivalent to 45 minutes to recharge the electric battery also It requires less maintenance and it has a longer lifespan.[Figure .5] illustrate how does a hydrogen fuel cell work while [Figure.6] show the design of hydrogen cars.

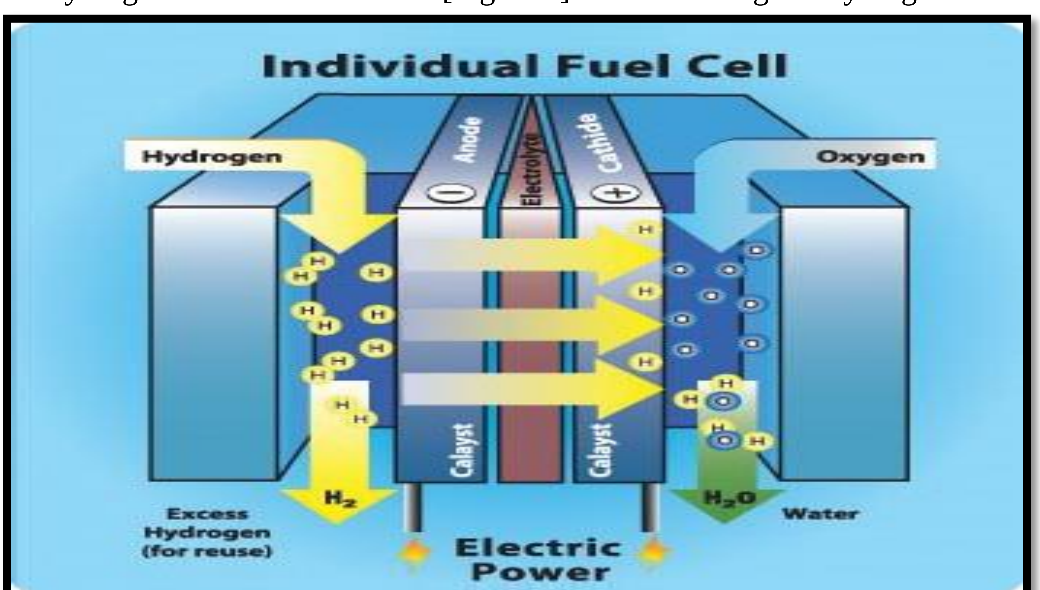

Figure.5. illustrate how does a hydrogen fuel cell. [20]

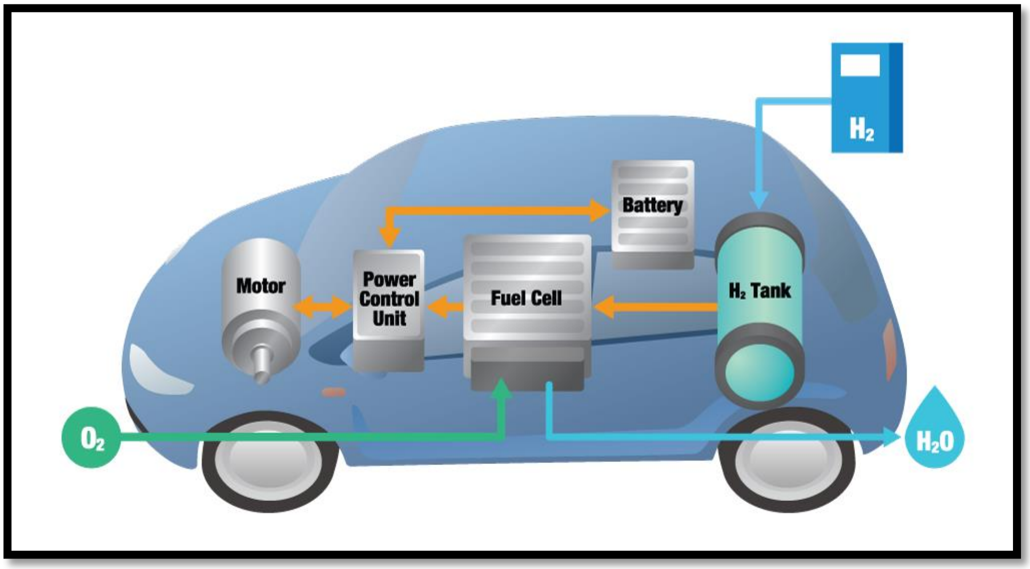

Figure.6. illustrate hydrogen cars. [21]

5-1 Differences between Hydrogen Fuel cells and water splitting:

Hydrogen Fuel cells can be defined as cells that convert chemical energy into electrical energy, and their principle of operation is the opposite of the principle of the electrolysis cell, where fuel cells work to make hydrogen interact with oxygen to generate electrical energy, while electrolysis cells work to analyze water molecules by the electric current into Hydrogen and oxygen, Its'worth noting that green hydrogen fuel cells are environmentally friendly, [Figure.7] illustrate the differences between water electrolysis and fuel cell. [22]

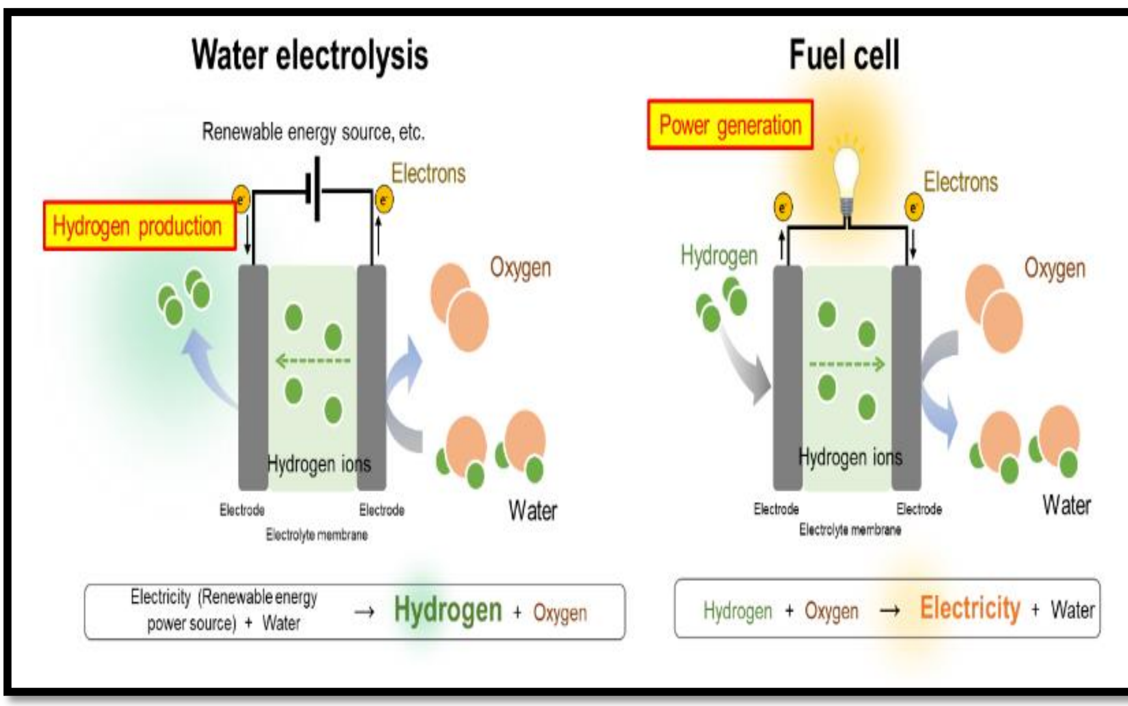

Figure.7. The differences between electrolysis and water splitting. [23]

6-1 Challenges of green hydrogen: [24-28]

1-6-1 Cost of Green hydrogen production

The cost of producing green hydrogen is very high, because obtaining energy from renewable sources, which is essential for generating green hydrogen through electrolysis, is more expensive if compared with the cost of producing hydrogen from non-renewable sources of energy.

2-6-1 Infrastructure

Scientists mentioned in the past that the basis of the industrial revolution began with the use of non-renewable energy sources, which are fossil fuels, and throughout these years, the necessary infrastructure was established to use this type of fuel source. As for green hydrogen, it is still recent, which requires governments to provide the necessary infrastructure and a serious study for all requirements of green hydrogen as a fuel for the future.

3-6-1 Hard in carriage

One of the most important problems associated with the production of green hydrogen, which must be quickly resolved, is the transportation problem, as it is difficult to transport green hydrogen using pipelines and shipping containers because it has energy density of 2700 times less than gasoline, so we find that gasoline can be transported easily by using pipelines more than green hydrogen.

4-6-1 Green hydrogen storage

Perhaps one of the most important challenges facing green hydrogen is the methods of storing, as it is known that hydrogen is a highly flammable gas, it has been found that if hydrogen is stored as a gas, this process will need a high pressure of up to 700 times normal atmospheric pressure, which is an ultra-high pressure, and it also needs to be cooled at -250 C° if stored as a liquid. These requirements require an additional cost over the cost of production.

In addition to the above two methods, hydrogen can also be stored using materials, as there are three types of hydrogen storage materials, those in which hydrogen is stored on its surface, this method is called adsorption, and materials in which hydrogen is stored inside, and this method is called absorption, and finally, hydride storage, which includes the use of Solid and liquid materials.

Although this method of storage provides many advantages such as storing hydrogen by using materials of small volumes, under low pressure, and at room temperature, this method is still under development due to the high cost of shipping, unloading, and hydrogen processing and in addition, it requires a very long time.

Also, green hydrogen can be stored in Salt caverns, exhausted oil and gas fields, or aquifers can all provide underground hydrogen storage on an industrial scale, Cavern storage is most suitable for hydrogen storage but is also a very expensive option.

7-1 Is green hydrogen storage safe?

As it is known that all types of fuel have a certain level of danger associated with them, relying on three factors; The source of the flame, the oxidizing agent, and the presence of the fuel, but through the use of the correct safety controls and conditions, it is possible to reduce the risks of any type of fuel, including green hydrogen. [29]

In fact, green hydrogen has several advantages that make it safer than other fuels. It is non-toxic, and since it is lighter than air, it dissipates quickly into the atmosphere upon release. This property is very important because it means that the fuel will dissipate into the air in the event of an accident, instead of remaining in place and igniting, as is the case with petroleum, for example. [30]

However, there are still risks related to hydrogen. For example, hydrogen has a wide range of flammable concentrations in the air, which means that ventilation and leak detection are important for hydrogen systems. In addition, hydrogen burns with an almost invisible flame, so it is necessary to use special flame detectors. [31]

Conclusion

Through the above, it becomes clear that green hydrogen is the key to life through which scientists will overcome the challenges of environmental pollution and severe climate changes that resulted from the use of fossil fuels, where green hydrogen can be relied upon as an alternative fuel to fossil fuels through its production from renewable energy sources such as wind, hydro and solar energy without any emission of CO2, which is considered one of the causes of global warming, and therefore scientists will create a clean and safe environment for human and for all living beings, and this, requires all countries of the world to take the necessary measures and provide the required infrastructure to increase the area of scientific and applied studies that are concerned with green chemistry in a way in general and green hydrogen in particular.

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