Green hydrogen as a potential solution for reducing carbon emissions: A Review

Abstract

Hydrogen is one of the types of energy discovered in recent decades, which is based on the electrolysis of water in order to separate hydrogen from oxygen. These include grey hydrogen, black hydrogen, blue hydrogen, yellow hydrogen, turquoise hydrogen, and green hydrogen. Generally, hydrogen can be extracted from a variety of sources, including fossil fuels and biomass, water, or a combination of the two. Green hydrogen has the potential to be a critical enabler of the global transition to sustainable energy and zero-emissions economies. Worldwide, there is unprecedented momentum to realize hydrogen's long-standing potential as a clean energy solution. Green hydrogen is a carbon-free fuel and the source of its production is water, and the production processes witness the separation of its molecules from its oxygen counterpart in the water by electricity generated from renewable energy sources such as wind and solar energy. Green hydrogen is one of the most important sources of clean energy, which may be why it is called green hydrogen. It is a clean source of energy, and its generation is based on renewable energy sources, so no carbon gases are released during its production. Green hydrogen produced by water electrolysis becomes a promising and tangible solution for the storage of excess energy for power generation and grid balancing, as well as the production of decarbonized fuel for transportation, heating, and other applications, as we shift away from fossil fuels and toward renewable energies. Green hydrogen is being produced in countries all over the world because it is one of the solutions to reducing carbon emissions, and it is clean, environmentally friendly energy that is derived from clean renewable energy. However, due to the combination of renewable generation and low-carbon fuels, projects for the production of green hydrogen are very expensive. The goal of this review is to highlight the various types of hydrogen, with a focus on the more practical green hydrogen.

Keywords: Green hydrogen, electrolysis, renewable energy, hydrogen types, economics.

1. Introduction

"Hydrogen is the most abundant element on the planet, and it is found primarily in water and organic compounds" [1]. "Because hydrogen atoms do not exist on their own, they require energy to produce hydrogen. Hydrogen is abundant in the form of water or natural gases, but in order to produce pure hydrogen, those molecular bonds must be broken using some form of energy. Currently, almost all hydrogen is produced using fossil fuels, with 76% coming from natural gas steam reforming and the remainder from coal gasification. Carbon capture and storage (CSS) and electrolyzers, for example, are expected to gain popularity due to their ability to reduce the environmental impact of hydrogen production. However, because these technologies are still in their early stages, their production costs are significantly higher than those of fossil-fuel-based hydrogen. As a result, adoption of these technologies is not anticipated until the upcoming years. One alternative to fossil fuels is green hydrogen, which can be produced through water electrolysis by splitting water into hydrogen and oxygen using an electric current with no greenhouse gas emissions, provided the electricity used to power the process is entirely renewable" [2,3]. "It can be used as a chemical feedstock, burned for heat, used as a reagent in the production of synthetic fuel, or converted back to electricity via fuel cells. Furthermore, hydrogen's long-term energy storage capacity in tanks or underground caverns makes it one of the only green technologies capable of storing energy over multiple seasons. As a result, many prominent scientists and economists have proposed a future in which gas will be the primary solution. Green hydrogen can provide clean energy to major economic sectors such as

industry, buildings, and transportation" [4,5]. As a result, the Paris Agreement's goal of achieving a 40% share of electricity as the dominant energy carrier by 2050 will be more likely to be realized [6]. Green hydrogen energy carriers allow large amounts of renewable energy to be directed from power systems into end-use sectors. There are several types of hydrogen, each distinguished by its production method, green hydrogen, white hydrogen, Grey hydrogen, Turquoise hydrogen, yellow hydrogen, Pink hydrogen and blue hydrogen are the different types of hydrogen under consideration. Each of these types is discussed briefly below in table 1.

Table 1: Production of hydrogen types by different processes.

Type of hydrogen	Process	Source	Color
Green hydrogen	Electrolysis	Renewable electricity	Green
White hydrogen	Naturally-occurring geological hydrogen	Found in underground deposits and created through fracking.	White
Grey hydrogen	Steam methane reforming (SMR) / Gasification	Methane / Coal	Grey
Yellow hydrogen	Solar power electrolysis	Mixed sources based on availability (from renewables to fossil fuels)	Yellow
Turquois hydrogen	Pyrolysis	Methane	Turquois
Blue hydrogen	steam methane reforming (SMR) / Gasification with carbon capture (about 95%)	Methane / Coal	Blue
Black hydrogen	Gasification	Black coal or lignite (brown coal) in the hydrogen-making process.	Black

2. Types of hydrogen

a) Green hydrogen

"Green hydrogen is the name given to hydrogen produced by electrolyzing water with clean electricity generated from surplus renewable energy sources like wind, solar, etc. Green hydrogen production is environmentally friendly and sustainable because it produces no greenhouse gas emissions. Green hydrogen emits much less CO2 than grey hydrogen, which is produced by steam reforming natural gas and accounts for the vast majority of the hydrogen market. Green hydrogen generated through water electrolysis accounts for less than 1% of total hydrogen production" [7]. "It could be used to decarbonize difficult-to-electrify industries such as steel and cement production, thereby assisting in the mitigation of climate change" [8-10]. "Electrolysis takes place within an electrolyzer. This is made up of an anode and a cathode separated by an electrolyte. These collect the individual elements through attraction, with positively charged hydrogen ions attracted to the negatively charged cathode and negatively charged oxygen ions attracted to the positively charged anode" (Fig 1) [11].

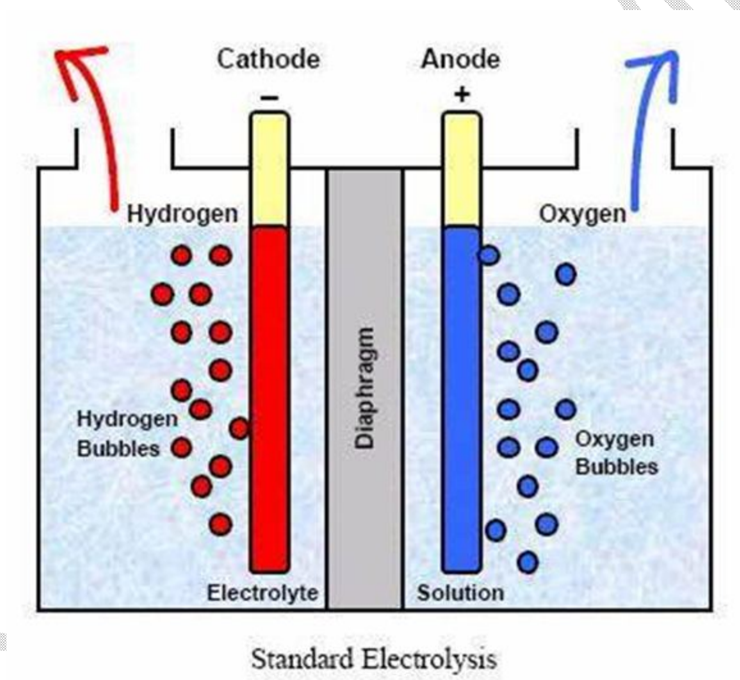

Fig. 1: The electrolysis principle for producing green hydrogen.

b) White hydrogen

White hydrogen is a naturally occurring geological hydrogen found in underground deposits that is produced by fracking. There are currently no plans to exploit this hydrogen. Clean white hydrogen can be produced from end-of-life plastic or other renewables via thermo-chemical steam conversion, a process that devolatilizes end-of-life plastic. The resulting hydrogen-rich synthesis, gas from this process is processed with pressure swing adsorption (PSA) or membrane separation to yield high purity clean white hydrogen and minor hydrocarbons, and the off-gas from the PSA process is used to generate energy for this Thermo-chemical conversion process, making it fully self-sufficient and sustainable without greenhouse gas emissions. Another advantage of this process is that it eliminates or reduces the global plastic waste problem [12].

c) Purple hydrogen

"Purple hydrogen is created by combining nuclear power and heat to split water using combined chemo thermal electrolysis" [13].

d) Red hydrogen

"Red hydrogen is created through high-temperature catalytic water splitting with thermal nuclear power as an energy source" [13].

e) Grey hydrogen

"The term "grey hydrogen" generally refers to hydrogen derived from fossil fuels. The most common type of grey hydrogen is extracted from natural gas using processes such as "steam methane reforming" (SMR) and "autothermal reforming" (ATR). These processes extract hydrogen from hydrocarbons by splitting natural gases into hydrogen and CO_2" [14-16]. While producing grey hydrogen, some greenhouse gases are not captured and released into the atmosphere.

f) Blue hydrogen

"Blue hydrogen is hydrogen produced from fossil fuels using the same processes as grey hydrogen, but with carbon capture and storage (CCS) to offset the levels of carbon dioxide released into the atmosphere. Because CCS cannot capture all of the carbon dioxide, blue hydrogen is referred to as a 'low-carbon hydrogen' alternative. The cost of blue hydrogen is expected to rise as a result of rising natural gas prices and carbon taxes" [15,17]. Companies are also attempting to use the captured carbon in a process known as carbon capture, storage, and utilization (CCSU). It is not necessary to use blue hydrogen to qualify for it. The blue hydrogen production process is carbon neutral because no CO_2 is emitted. Blue hydrogen is also known as low-carbon hydrogen.

g) Pink hydrogen

"Pink hydrogen is produced through nuclear-powered electrolysis, but this method is limited by low efficiency and poor economics. Other names for nuclear-produced hydrogen include purple hydrogen and red hydrogen. Pink hydrogen is the most dangerous long-term option, with short-term gains in additional generating capacity to produce hydrogen gas via electrolyzers. It is unsustainable and one of our least preferred options for achieving a circular economy. The radioactive toxic waste is dumped into the oceans, where it will remain a potential biological hazard for (almost) indefinitely. As a result, exploitation could never be circular, in which sustainable practices are neutral and do not pose a long-term risk" [18,19].

h) Turquoise hydrogen

"Turquoise hydrogen is produced through a process known as methane pyrolysis, which generates hydrogen and solid carbon. Turquoise hydrogen may be valued in the future as a low-emission hydrogen, assuming that the thermal process is powered by renewable energy and that the carbon is permanently stored or used" [20].

k) Yellow hydrogen

"Yellow hydrogen is a relatively new phrase for hydrogen made through electrolysis using solar power. This method of producing hydrogen is relatively new. Other mixed energy sources are sometimes used to produce yellow hydrogen" [21].

l) Black or brown hydrogen

Black hydrogen is hydrogen produced by gasifying bituminous coal, or converting a fossil fuel into a more useful energy carrier. However, converting coal to hydrogen is neither environmentally friendly nor an efficient use of resources when it comes to cooling the planet. Black hydrogen is dirtier than Grey, Blue or Turquoise hydrogen. Yellow or green hydrogen, produced from renewable electricity, is the cleanest form of hydrogen production. The oldest method of producing hydrogen is to convert coal into gas. Gasification processes produce carbon monoxide, hydrogen, and carbon dioxide from organic or fossil-based carbonaceous materials. Gasification occurs at extremely high temperatures (greater than 700°C), without combustion, and with a controlled amount of oxygen and/or steam. Through a water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen. Syngas is the gas produced by coal gasification, and hydrogen can be separated from the other elements using adsorbers or special membranes. Depending on the type of coal used, this hydrogen is either brown (lignite) or black (bituminous). Because CO2 and carbon monoxide cannot be reused, they are released into the atmosphere. This is a very dirty way of producing hydrogen, it is unsustainable, and it is one of the least appealing options for creating a circular economy. This type of hydrogen production is the most harmful to the environment [22]. The evaluation of the environmental rating of different hydrogens is shown in table 2.

Table 2: Evaluation of Environmental rating of different hydrogens.

Type of hydrogen	Method	Environmental rating
White hydrogen	Naturally occurring	Clean
Green Hydrogen	Renewable electrolysis	Clean (created with renewable energy sources)
Yellow hydrogen	Solar power electrolysis	Clean
Blue hydrogen	Steam reformation	Dirty
Turquoise hydrogen	Methans pyrolysis	Moderately clean
Pink hydrogen	Nuclear powered	Moderately clean
Grey hydrogen	Steam reformation	Dirty
Purple hydrogen	Nuclear powered and heat	Moderately clean
Red hydrogen	Thermal nuclear power (biogas with capture and storage of CO_2)	Moderately clean
Brown hydrogen	Coal gasification	Not climate friendly
Black hydrogen	Coal gasification	Not climate friendly

3. Hydrogen economy

"Green hydrogen, which is produced using renewable resources such as solar and wind, holds great promise for meeting the world's future energy needs. However, the economics of green hydrogen is currently challenging, owing to wide variations in the underlying costs and availability of renewable energy sources. Currently, almost all hydrogen produced in the world is "grey," which means it is

derived from natural gas. Green hydrogen, on the other hand, is more expensive than grey hydrogen and uses renewable energy to power electrolysis, which separates water molecules into hydrogen and oxygen. Green hydrogen is a better long-term solution to help decarbonize economies because it does not require fossil fuels" [23]. "Green hydrogen production markets with abundant, low-cost renewable resources are the most appealing. Green hydrogen could currently be produced in parts of the Middle East, Africa, Russia, the United States, and Australia. The lowest cost is most easily attained in areas with access to low-cost renewable energy plants" [24]. "However, production costs will fall over time as a result of continuously falling renewable energy production costs, economies of scale, experience gained from ongoing projects, and technological advancements. As a result, green hydrogen will become less expensive" [25]. "Countries must begin pilot projects as soon as possible in order to gain practical experience and capitalize on efficiencies gained through learning curves and design models on production equipment such as electrolyzers. It is essential to create projects now to ensure continuous demand growth, which justifies the implementation of the needed hydrogen infrastructure to meet future greenhouse gas reduction targets" [26,27]. "The hydrogen economy employs hydrogen to decarbonize economic sectors that are difficult to electrify, such as cement, steel, and long-distance transportation. Hydrogen can be created from water using renewable sources such as wind and solar, and its combustion only emits water vapor into the atmosphere, allowing us to phase out fossil fuels while limiting climate change" [14]. "Hydrogen is an energetic fuel that is frequently used as rocket fuel, but numerous technical challenges prevent the development of a large-scale hydrogen economy. These include the difficulty of developing long-term storage, pipelines, and engine equipment such as a relative lack of off-the-shelf engine technology that can currently run safely on hydrogen, safety concerns about the high reactivity of hydrogen fuel with oxygen in ambient air, the cost of producing it via electrolysis; and a lack of efficient photochemical water splitting technology. hydrogen can also react in a fuel cell, which efficiently produces electricity in a process that is the opposite of water electrolysis" [16,28]. "A possible less-polluting alternative is the newer technology of methane pyrolysis though SMR with carbon capture and storage (CCS) may also greatly reduce carbon emissions. Small amounts of hydrogen (about 5%) are produced by the dedicated production of hydrogen from water, usually as a byproduct of the process of generating chlorine from seawater" [29]. "The idea of the hydrogen economy has been heavily criticized from the moment it was proposed" [30]. "The main issues with the hydrogen economy scenario are as follows:1) The human civilization does not have a clean, energy-efficient and low-cost source of Hydrogen. 2) Storage of Hydrogen within a transportation vehicle for its motive power faces cost and safety issues. 3) Conversion of Hydrogen into electricity in fuel cells have low energy efficiency, with issues of durability and cost remaining unresolved" [31].

4. Discussion

"Most experts agree that green hydrogen will be essential to meeting the goals of the Paris Agreement, since there are certain portions of the economy whose emissions are difficult to eliminate. In the U.S., the top three sources of climate-warming emissions come from transportation, electricity generation and industry" [32]. "Hydrogen can be produced by electrolysis of water, leaving only oxygen as a byproduct. An electrolyzer uses an electric current to split water into hydrogen and oxygen. If the electricity is generated using renewable energy sources such as solar or wind, the resulting pollutant-free hydrogen is known as green hydrogen. One reason for the growing interest in green hydrogen is the rapidly decreasing cost of renewable energy. Hydrogen has numerous applications. Green hydrogen has industrial applications and can be stored in existing gas pipelines to power household appliances. When converted into a carrier such as ammonia, a zero-carbon fuel for shipping, for example, it can transport renewable energy" [33]. "Hydrogen can also be used in conjunction with fuel cells to power electrical devices such as electric vehicles and electronic devices.

In addition, unlike batteries, hydrogen fuel cells do not need to be recharged and will not run out of hydrogen fuel. Hydrogen fuel cell vehicles are powered by hydrogen. A hydrogen fuel cell is two to three times more efficient than a gas-powered internal combustion engine due to its high energy efficiency. Refueling a fuel cell electric vehicle takes less than four minutes on average. Many researchers believe that green hydrogen will be widely used in the next five to ten years, particularly in Europe and Japan. However, they believe that the limits of existing infrastructure both pipeline infrastructure and transmission lines will be reached very quickly, because producing green hydrogen will require about approximately 300 % more electricity capacity than we currently have. "We will reach limits in electrolyzer manufacturing, electricity infrastructure, port capacity to make and ship the stuff, and the speed with which we can retrofit industries” [34,35].

5. Conclusion

Implementing hydrogen as a zero-emission fuel is not enough to combat global warming; we must now switch to the only oxygen and water balanced fuel: green hydrogen. Using hydrogen derived from fossil fuels results in a net decrease in atmospheric oxygen and a net increase in water vapor, regardless of whether CCS is used in the production process. In contrast, hydrogen derived from water electrolysis neither depletes oxygen nor increases water vapor and CO_2 concentrations in the atmosphere. As a result, it is critical to avoid viewing blue, turquoise, and green hydrogen as interchangeable. It is not valid to compare these types of hydrogen solely on the basis of CO_2 footprint, because they have markedly different effects on atmospheric oxygen and water vapor. Green hydrogen, not blue or turquoise hydrogen, should be prioritized by policymakers and governments. Future efforts to combat climate change should include the deployment of electrolyzers with large installed capacities. This will slow the rate of oxygen depletion and provide us with a fuel with a low environmental impact, assuming that the energy system is designed to minimize hydrogen leaks and releases. The solution to the O_2 and CO_2 concentration problems is to reduce the use of fossil fuels and avoid using fossil fuels to produce hydrogen. The global ecosystem now necessitates the extraction of hydrogen and oxygen from water. Achieving a large number of multi-electrolyzer capacities by 2050 would have a massively positive impact on climate change mitigation.

ACKNOWLEDGEMENT

Authors acknowledge the support provided by the National Research Centre (NRC), Egypt, and the Egyptian Petroleum Research Institute (EPRI).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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