CHAPTER ONE

AN INTRODUCTION TO DIFFERENT TYPES OF HYDROGEN AND METHODS OF GREEN HYDROGEN PRODUCTION

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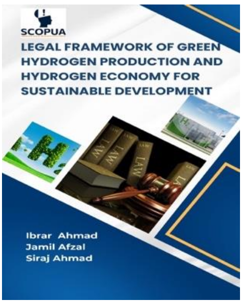

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Abstract

Hydrogen is gaining prominence as an important clean energy carrier with the potential to cause a transformation in the world as it shifts to sustainable, low-carbon energy systems. In this chapter, the author will provide a vivid description of the various types of hydrogen, distinguished by their production technologies and environmental friendliness, including grey, blue, turquoise, pink, and green. The focus is on green hydrogen produced through the electrolysis of water by using renewable energy sources, including solar and wind. Green hydrogen is a zero-emission solution with huge potential to decarbonise sectors that are difficult to electrify, such as heavy industry, transportation, and power generation. The chapter discusses important technologies of green hydrogen production, such as proton exchange membrane (PEM), alkaline, and solid oxide electrolysers, and further advanced systems such as PV/T-electrolysis, wind-electrolysis, biological, and thermochemical processes. The efficiency, scalability, cost, and renewable energy integration are considered with regard to each technology. In addition, the paper discusses the key obstacles to green hydrogen, including the high cost of production, infrastructure requirements, and technology maturity. Nevertheless, with the increasing global emphasis on net-zero goals, a drop in renewable energy prices, and a swift technological improvement, green hydrogen can become the foundation of a clean energy future economy.

Keywords: *Green Hydrogen; Hydrogen Production; Hydrogen Production Methods; Hydrogen for Sustainable Development; Types of Hydrogen*

1.1. Introduction

The increase in global energy demand that is clean, secure, and sustainable energy has influenced the increased rate of abandoning fossil fuels [1]. In this regard, hydrogen has turned out to be a strategic energy carrier that could transform many energy systems in the transport, production, electricity, and chemical sectors [2]. It is versatile because Hydrogen can store, transport, and deliver clean energy when generated using renewable energy sources [3]. An example is the hydrogen fuel cell, which produces only water and heat and thus is very appealing as a zero-emission solution, both in mobile and stationary applications. In addition, hydrogen is applicable in combustion engines, synthetic fuels, ammonia generation, and long-term energy storage. These properties make hydrogen a pillar of the new energy system, especially in hard-to-electrify industries or those that are inefficient to electrify directly. But it is not the element hydrogen itself that defines its sustainability and environmental friendliness, since hydrogen does not occur naturally in its pure form, but rather how it is produced. Currently, most of the world's hydrogen comes into being based on fossil sources, mainly natural gas, in the form of so-called steam methane reforming (SMR) [4]. This type of hydrogen is referred to as grey hydrogen, and it results in high carbon dioxide emissions, thus offsetting the green advantages of hydrogen consumption. Another form, blue hydrogen, applies the same method with the addition of storing and capturing (CCS) the emissions of CO_2. Although blue hydrogen is much cleaner than grey, it is indirectly linked to fossil fuel resources and infrastructure [5]. By comparison, green hydrogen is produced in an electrolysis of water process, as done through renewable electric power, e.g., solar power or wind energy [6]. There are no greenhouse gases produced in this process, and so indeed green hydrogen is a clean, sustainable solution, which can meet the decarbonization targets set globally [7]. Green hydrogen has gained importance as the urgency of climate change mitigation and energy transition policies has risen [8]. Countries globally, and particularly those bound toward net-zero goals, are rushing to invest in green hydrogen technologies in an attempt to decarbonise heavy industry, including steelmaking, cement production, and petrochemical refining, which is presently dependent on carbon-intensive fuels. Green hydrogen also has potential solutions to sectors that are difficult to electrify, including long-haul trucking, maritime shipping, and aviation, either as a foundation for synthetic fuels or direct propulsion [9]. Furthermore, green hydrogen is a possibility of balancing the electricity grids, where hydrogen can be used to fill the peaks and valleys of the supply and demand world, since it is a material through which the surplus electricity generated when nobody needs electricity can be stored and the release of then same can be released when everybody wants electricity. Such features not only assist environmental ambitions but also improve energy security and provide economic potential by establishing new hydrogen-based industries.

Nevertheless, the prospect of green hydrogen production is threatened by several technological and economic issues [10, 11]. Electrolysis is the primary technology of green hydrogen production, which consists of the disintegration of water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electric energy. The most common types of electrolysers in use are alkaline electrolysers, proton exchange membrane (PEM) electrolysers, and solid oxide electrolysers (SOECs). The most developed and widespread technology is alkaline electrolysers, which are considered economical and scale well [12]. PEM electrolysers are more costly but more efficient, have a faster response time, and can be integrated more easily with variable renewable energy sources. SOECs work at high temperatures and promise perhaps even higher efficiencies, although they are still early in commercialisation [13, 14]. In addition to these, scientists are working on better materials, catalysts, and system architectures that will enhance performance, reduce cost, and increase durability. Moreover, there are moves to combine green hydrogen production with decentralised renewable energy generation, including solar farms and offshore wind platforms, to make self-sufficient hydrogen production modules.

This chapter explains the hydrogen classification by production means, with the differences between grey, blue, turquoise, and green hydrogen being noted. Particular interest is devoted to green hydrogen because it can contribute to achieving sustainability and decarbonization goals. Further, the article addresses technological approaches to green hydrogen production, compares the merits and drawbacks of all processes, and elaborates on their applicability in industry. With the world of energy rapidly changing, it is important to realise the various types and the mechanisms that facilitate green hydrogen production. In this discussion, the chapter tries to provide insight into why hydrogen is a vital element in ensuring a faster switch to a cleaner, more flexible, and future-ready energy system.

1.2. Hydrogen Production

Fossil hydrocarbons are catalytically cracked under steam (H_2O) conditions at 700-900 ^{0}C and 3-35 bar pressure to produce hydrogen (H_2) and carbon monoxide (CO) [15]. The most widely used heterogeneous catalysts are nickel (Ni), precious metals alloy like Ni/Al_2O_3 or Ru/ZrO_2 [16, 17]. As a hydrocarbon feedstock, natural gas is frequently utilised on an industrial scale. The main substance of natural gas is Methane (CH_4) with its molar fraction of 75.99 per cent. This is why this process is commonly known as steam methane reforming (SMR). Besides methane, natural gas also contains, in variable amounts, higher alkanes (ethane, propane, butane), inert gases (nitrogen, helium), and early so-called sour gases (carbon dioxide, the main, and hydrogen sulfide). Especially harmful is hydrogen sulfide (H_2S) included in the feed to downstream processes, because sulfur compounds poison catalysts, chemisorbing on the metal centers of the active surface area of catalysts [18]. As such, H_2S ought to be removed during the hydrocarbon feed. H_2S is normally eliminated during hydrotreating or absorption on activated zinc oxide [19]. The feed is then subjected to proper pre-treatment, and the steam reforming stage is then activated. The overall hydrocarbon conversion and the methane conversion in specific terms are captured by the chemical equations given in Eqs. 1 & 2, respectively. The reaction is very exothermic and will, thus, need great access to an external heat source. The heat is added to the system as steam and/or by heating the reactor externally. Natural gas and off-gases during hydrogen purification are common fuels. Moreover, the exothermic water-gas shift (WGS) reaction (Eq. 3), whose heat can be combined with the next stage of the chain of SMR.

$$C_nH_m + n\ H_2O \rightleftarrows n\ CO + (n + m/2)\ H_2 \quad (1)$$

$$CH_4 + H_2O \rightleftarrows CO + 3\ H_2\ \Delta H^0{}_R = +206.3\ kJ/\ mol \quad (2)$$

$$CO + H_2O \rightleftarrows CO_2 + H_2\ \Delta H^0{}_R = -41.2\ kJ/\ mol \quad (3)$$

High temperatures, low pressures as applied using Le Chatelier's principle, and the addition of extra steam help to improve the SMR performance in an attempt to avoid the formation of coke. The latter is represented in the ratio between steam and carbon. Common ratios are 2-5, and 2.5-3.5 ratios have often been cited as an optimal ratio of purified H_2 yield, efficiency, and plant size. Future development of SMR specifically aims at improving energy efficiency of steam pre-heating with Low intensity of fuel consumption and higher outlet temperature of the reformer. SMR is a mature and well-developed technology (TRL 9) [20, 21]. The largest ones have a capacity of up to 120,000 Nm^3/h H_2 production and downstream produce ammonia (NH_3). SMR of higher heating value (HHV) has a total process efficiency of between 65-70 percent [22, 23].

1.2.1. By-product steam

The steam, which is the overflow heat in the convective section of flue gas and the partial cooling of the product stream, can be sold to supply steam to the adjacent industrial plants or air in steam turbines. On an HHV basis, the estimated limit of process efficiency of SMR based on the practical process is 88.9 - 90.7%.

1.2.2. Carbon capture and storage-based steam methane reforming

There are indicators that carbon capture and storage (CCS) technologies can be used to restrain process-related CO_2 emissions and provide the production of low-CO_2 hydrogen. The process of production and the resources of fossils used by SMR-CCS are entirely the same as those used by grey H_2, hence the name SMR-CCS. The resulting part of CO_2 is mostly captured and stored in geological sites instead of being released into the atmosphere. Because most of the direct CO_2 emissions are avoided in this manner, H_2 made with SMR-CCS is occasionally described as low-CO_2 or blue H_2, though never when the captured CO_2 is not stored.

1.2.3. Methane pyrolysis

In methane pyrolysis (MP), the so-called methane decomposition and methane cracking, CH_4 is decomposed (cracked) to release gaseous H_2 and elemental carbon (C).

$$CH_4 \rightleftarrows 2\ H_2 + C\ \Delta H^0{}_R = +74.9\ kJ/\ mol \quad (4)$$

Just like the SMR, in this case, too large amounts of CH_4, which is produced predominantly in the form of natural gas and, hence, is a fossil-fuel hydrocarbon source, are used. Even more CH_4 volumes are required to generate hydrogen utilising MP, with the consideration that the H_2/CH_4 molar ratio is 2:1 as compared to 4:1 in SMR. The CO_2 emissions are, however, not directly caused by MP. Therefore, H_2 derived by MP is occasionally termed as CO_2-free or turquoise H_2. It has been reasoned as having the potential of becoming a bridging technology to the climate-friendly production of hydrogen when using MP.

1.2.4. Natural gas as a feedstock

The industrial application of MP first applies to natural gas. Eventually, methane generated by the biogas plant can also be utilised. A limited number of studies have, however, been associated with the effect posed by the trace components in the feed gas on the key process variables such as the selectivity, the product quality, and the conversion. Nickel and iron-based Catalysts get more deactivated the more they are exposed to H_2S. Low concentrations of higher alkanes may have no negative, or indeed, a positive effect on CH_4 conversion, and their minimisation can reduce carbon catalyst deactivation. The removal of contaminants such as N_2 is important during natural gas processing[24], as components other than CH_4 may react to form undesirable byproducts, including saturated and unsaturated hydrocarbons, as well as polycyclic aromatic compounds. Hence product hydrogen stream may need to be purified, in cases where the hydrogen is to be utilised in sensitive processes, e.g., utilisation in fuel cells and in the chemical industry as a feedstock.

1.3. Types of Hydrogen

Hydrogen, in its end-use form, is chemically identical, but varies greatly concerning environmental impact, based on the method of production [25]. To simplify these distinctions, hydrogen is often categorised using colour codes which indicate its route of production and the carbon footprint it has. The significant forms of hydrogen are grey, blue, and green hydrogen, and the other upcoming classes are turquoise, pink, yellow, and white hydrogen. Each of these types is marked with different technological, economic, and ecological features.

1.3.1. Blue Hydrogen

Blue hydrogen is a low-carbon hydrogen produced through natural gas via steam methane reforming (SMR) or autothermal reforming (ATR) process, with the carbon capture, utilisation, and storage (CCUS) operation [26]. Here, the hydrogen is taken out of methane, and the carbon dioxide produced is stored and captured underground or utilised in industries, thus it does not escape into the atmosphere. Although blue hydrogen is much better at minimising greenhouse gas emissions compared to grey hydrogen, it is not zero-emission, since carbon capture systems are not perfect, and methane may leak during natural gas production and transportation. Blue hydrogen is occasionally viewed as a stopgap, a means of gradually scaling down the fossil-based production of hydrogen we have now to the widespread usage of green hydrogen, which is made using renewable energy sources in the future.

The carbon dioxide byproduct is never associated with the manufacture of hydrogen by the use of fossil fuels. The carbon footprint of the fossil-based hydrogen production is very sensitive to the kind of feed used as well as the technology used in the production [27]. The future of the blue hydrogen market is also predetermined by the prices of the fossil fuels, the nature of the global energy system, and the regulations on carbon emissions [28]. Traditionally, the most widely used feedstock in the production of hydrogen was natural gas and liquid petroleum. All that, however, was altered with the increase in the production of natural gas and the increased demand for transportation fuels in the past 30 years, and both hydrogen and syngas production shifted to natural gas and coal, with the use of liquid petroleum as a hydrogen feedstock much lower in the ranking chart. Blue hydrogen is generated using fossil fuels, mainly natural gas, by using reactions like steam methane reforming (SMR) or autothermal reforming (ATR), and it has carbon capture and storage (CCS) to limit the carbon emissions released during hydrogen production significantly. In steam methane reforming, reforming of methane takes place in the presence of steam at elevated temperatures to yield hydrogen and carbon dioxide. With blue hydrogen, the CO_2 by-product is captured and either stored in underground geological structures or reused in industry, rather than being emitted to the atmosphere [29, 30]. This results in blue hydrogen being a low-carbon alternative to grey hydrogen, which takes the same production route but releases CO_2 directly. However, blue hydrogen is not carbon-free. CCS systems have varying efficiency, and some percentage of carbon emissions could still be released to the environment. Moreover, natural gas extraction, processing, and transportation may lead to methane leakages, which is a highly efficient greenhouse gas and causes serious problems with climate change. Such aspects have prompted the discussion of whether blue hydrogen is environmentally beneficial at all. Nevertheless, blue hydrogen is frequently regarded as a practical and transitional method of cutting emissions in the short-term to medium-term. It also utilizes the existing natural gas infrastructure and enables the scale deployment of hydrogen to be rolled out as green hydrogen technologies are still maturing. In nations possessing large quantities of fossil fuels and CCS potential, blue hydrogen provides a means to start decarbonising energy systems without having to await the large-scale availability of renewable-based options. In this respect, blue hydrogen can be considered a bridge technology, allowing a slow transition to a cleaner energy system, with the path being open to the scale-up of green hydrogen, produced by electrolysis with renewable energy, with zero direct emissions.

1.3.2. Green Hydrogen

Internally produced green hydrogen is the product of electrolysis, or the ability of energy in the form of electricity to split the water (H_2O) into hydrogen (H_2) and oxygen (O_2) [31, 32]. When such electricity is generated purely using renewable power resources solar power and wind, then the resulting hydrogen is said to be green since no greenhouse gases are emitted in the process. Electricity is generated in solar panels or wind turbines, and this electricity is used to operate an electrolyser, which is a device where the water-splitting reaction occurs. The process results in zero direct emissions of hydrogen as an energy carrier, which is truly clean. Production of hydrogen by wind and solar is particularly appealing since these renewable resources are plentiful, sustainable, and rapidly becoming cost-competitive. With the ever-increasing solar and wind power capacity in the world, the combination of these energy sources with electrolysers makes decentralised and scalable green hydrogen production possible. This form of hydrogen will play an important role in the decarbonisation of those sectors that are challenging to electrify (heavy industry, aviation, long-range transport) and offering a renewable way of energy storage of any excess renewable electricity and the balancing of power grids.

Two significant components make up the green hydrogen system: the renewable energy source and the water electrolyser. The basic equation of water decomposition is given:

$$H_2O\ (\text{Liquid}) + \text{Energy} = H_2\ (g) + \tfrac{1}{2}\ O_2\ (g) \quad (5)$$

Electrical energy makes use of a DC power source. The water electrolysis technology can be divided into three categories based on the nature of the electrolyte used in the cells: Liquid electrolyte: alkaline water electrolyser, alkaline anion exchange membrane. Acid ionomer: proton exchange membrane electrolyser and solid polymer electrolyser, in which electrolysis takes place. High temperature steam electrolyser and solid oxide electrolyser (Steam electrolysis), high temperature steam electrolyser and solid oxide electrolyser (HTSE and SOE) [33].

The PEM (Proton Exchange Membrane) contains electrodes and electrolytes, and the materials that have been used as the electrodes are platinum, iridium, and ruthenium. A small design and a high conductivity of the protons and high pressure (15 to 30 bar at 50 to 90 °C) denote the PEM [34]. The advantages of the PEM are associated with its rapid response rate and that it produces high-purity hydrogen (99.999 percent). Its disadvantage, however, is that it is very expensive since noble material is used in the electrolysis.

The AWE (Alkaline Water Electrolyser) is an electrolyser that is comprised of a diaphragm and two electrodes immersed in a silver-coloured electrolyte water solution that typically contains almost 40 percent of sodium hydroxide (NaOH) or potassium hydroxide (KOH) [35, 36]. The diaphragm that divides the two electrodes in the solution enables the flow of water molecules and the hydroxide ions and separates the H_2 and O_2 due to the aspects of safety and purity concerns. Hydrogen produced has a purity of 99.5 to 99.9 per cent, which can further be up to 99.99 per cent through the application of catalytic purification of gases. Performance of this type of electrolysis is influenced by the diaphragm, the type of anode and cathode material, and the thickness. The features of AWE and the PEM apply here in that AWE utilises a volatile liquid electrolyte, whereas the PEM utilises a solid polymer membrane electrolyte.

The AEM (Alkaline Anion Exchange Membrane) is assumed to be an amalgamation of the PEM and the AWE [37]. AEM is the conglomeration of the PEM and the AWE strengths. In such a way, the AEM operates at a low concentration alkaline solution rather than a 20-40% KOH or NaOH aqueous solution and solid electrolyte (polymeric) membrane. An anode in AEM is Ni-based (e.g., Ni foams), and the cathode has Ni, Ni-Fe, and $NiFe_2O_4$.

HTSE (High-Temperature Steam Electrolyser) refers to a high-temperature electrolyser, using steam [33]. The primary strength of this technology is that the disengagement of steam will use less amount of energy when compared to liquid water. The HTSE needs heat, as opposed to electric energy, to crack the water molecule. That is how it may be suggested to increase the efficiency of this process and reduce the cost of hydrogen manufacture.

Higher temperature is used in the SOE (Solid Oxide Electrolyser), and due to the low temperature of electrolysis, the electricity required to power its electrolysis is very little [14]. There is therefore an increase in the efficiency of the system since it makes use of low-cost thermal energy. The steam side on the cathode end of the hydrogen production unit of the SOE is subject to reduction to the hydrogen gas after the cathode reaction process, and subsequently, the oxide anions that are thus formed present the route in which the solid electrolytes combine to form the production of oxygen on the anode end.

1.3.3. Pink hydrogen

Pink hydrogen is a hydrogen production pathway that does not generate CO_2 directly [38]. Unlike green hydrogen, pink hydrogen is obtained as a result of electrolysis of water, and in contrast to the former, due to the assistance of electricity produced at nuclear power plants (NPP) [39]. Several advantages are associated with this move. Firstly, nuclear power is environmentally friendly in relation to other power sources. A nuclear energy global warming potential (GWP) is 0.027 kg CO_2 eq./kWh, and it is lower compared to that of natural gas, coal, oil, and renewable energy. Second, renewable energy costs more as compared to nuclear electricity. The weighted average levelized cost of energy (LCOE) of PV, onshore wind, and offshore wind was in 2021, reported by the International Renewable Energy Agency (IRENA) to be 0.048 $/kWh, 0.033 $/kWh, and 0.075 $kWh, respectively. The nuclear energy calculated LCOE was within the 0.015 $/kWh to 0.049 $/kWh range of reactors and countries, and its values were at par and even lower than the numbers of the renewable energy sources [40]. So, pink Hydrogen can be at least as cost-effective as green hydrogen and more so. Finally, it permits a constant and smooth provision of power. Typical hydrogen production technologies using pink electrolysis stand out as alkaline electrolysis (AEL), polymer exchange membrane electrolysis (PEMEL), and SOEC. Among them, SOECs show the highest-reported efficiency (81-86 %HHV) and are still not commercialized; they also can operate at elevated temperatures (600-1,000 °C) and thereby can recover waste heat. SOECs, however, are incapable of operating at their best during transient operation processes, as well as exhibiting low durability. In addition, electric heaters (EH) required in the process of producing high-temperature steam consume much power, resulting in a high cost of power. Therefore, serious research has been conducted to integrate SOEC with other processes to reduce power consumption.

1.3.4. Turquoise hydrogen

Compared to other means of producing hydrogen, turquoise hydrogen is one of the prospective green hydrogen production methods [41]. It is the endothermic pyrolysis of methane, and it needs lots of external sources of heat. Conventionally, pressure swing adsorption (PSA) purge gas is burned to provide this heat, which, however, introduces CO_2 emissions to the process [42]. Hence, the key to ensuring that turquoise hydrogen remains green is by ensuring the capture of the CO_2 emitted upon combustion. In this regard, oxy-fuel combustion has been considered as one of the technically feasible solutions, since it is thermally efficient and capable of capturing CO_2 effectively. It, however, requires a high-purity oxygen supply, which can only be produced at present by cryogenic air separation units (ASUs). Although they are reliable, ASUs are energy-consuming and lower the efficiency of the whole system, particularly when used with CO_2 compression and purification units (CPUs). Such demands induce economic challenges that will need to be solved with innovation or a combination with low-cost renewable power to realise a genuinely sustainable and commercially attractive route in the future hydrogen economy of 2025.

The most promising opportunity among the different technologies that exclude green and grey hydrogen is called turquoise hydrogen. It is produced through the pyrolysis of natural gas, and solid carbon is produced as a by-product. The Turquoise hydrogen possesses some advantages over other hydrogen production pathways. To begin with, the pyrolysis process is one step that does not require steam or even half of the feedstock required by the steam methane reforming (SMR). At room temperature, the enthalpy change of reaction per mole of hydrogen is 37.4 kJ/mol during the pyrolysis process, as compared to the results of SMR (41.3 kJ/mol) and the electrolysis value (285.83 kJ/mol) [43, 44]. It implies that turquoise hydrogen has an energy preference over the other hydrogen production pathways. Second, hydrogen of turquoise colour is environmentally friendly. The carbon of the natural gas is not released as CO_2, as is the case with the conventional pathways in the production of hydrogen. It is instead converted into solid carbon, thus there are no direct emissions of CO_2, but the energy used is also low, and there is no CO_2 emission. Monolith, the only global company to produce turquoise hydrogen, has the opportunity to reduce GHG by approximately 1 million tons compared to the conventional methods of manufacturing carbon black. Finally, economic viability can further be boosted by selling solid carbon, which will result as a by-product. Solid carbon may be produced in various forms, depending upon the catalysts and the operating conditions, as an amorphous form, carbon black, or nanofibers.

Black hydrogen is hydrogen gas, which is generated with coal, particularly bituminous coal or lignite (brown coal) as the main raw material [45]. It is produced by a chemical process called coal gasification, in which coal is heated to very high temperatures, usually between 1,200 °C and 1,500 °C, in a controlled atmosphere with little oxygen and steam. In this situation, the coal is broken down into a gas mixture called synthesis gas (syngas) that primarily consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and trace methane and other gases. The syngas is then further processed (using more chemical reactions and purification steps) to remove the hydrogen, e.g., the water-gas shift reaction converts CO and water into more hydrogen and CO_2. Although this is a way to mass-produce hydrogen, it is ranked as one of the uncleanest and least sustainable ways to do it. Black hydrogen has a great environmental effect. Each kilogram of hydrogen generated through coal yields an estimated 15 to 19 kilograms of atmospheric carbon dioxide emissions. Such an enormous carbon footprint turns black hydrogen into a major cause of climate change and air pollution. Besides, other harmful by-products are also generated during the process, including sulfur compounds, tar, heavy metals, and ash, which have to be well handled and treated to avoid contamination of soil and water. Most often, the coal gasification process does not have adequate carbon capture and storage (CCS) mechanisms, and this implies that the bulk of the CO_2 emissions are pumped directly into the atmosphere.

1.3.5. Black hydrogen

Despite these disadvantages, black hydrogen is still manufactured in several countries because of the cheap availability of coal. Countries like China, India, and South Africa are dependent on coal as a source of energy and industrial operation, and consequently, black hydrogen is largely preferred due to economic viability. It is mostly utilized in the production of ammonia (in fertilizers), methanol, petroleum refinery, and in the generation of electricity. Those economic benefits, however, are achieved at the cost of environmental sustainability, national health, and global climate commitments. With the world more interested in carbon emissions and climate change, black hydrogen is slowly being used as a technology of yesterday, and that is unsustainable. Conversely, more modern and clean methods of hydrogen production are being supported as long-term solutions in a low-carbon future: blue hydrogen (natural gas produced with carbon capture) and green hydrogen (water produced using renewable electricity). These ways are in contrast to black hydrogen, which has high or no prospect of low or zero emissions and hence are more aligned with national and international net-zero targets. Overall, black hydrogen is the carbon-intensive mode of hydrogen production, namely, coal-based economies [46]. Although it can bring short-term economic gains to coal-rich areas, it has enormous environmental and health costs. With the world shifting towards cleaner energy systems, it is anticipated that the production and utilisation of black hydrogen will decrease, making way for sustainable and renewable hydrogen technologies, which are in line with the global trend of decarbonization. Different types of hydrogen, based on production methods and energy sources, from fossil-based, are given in the following Figure 1.

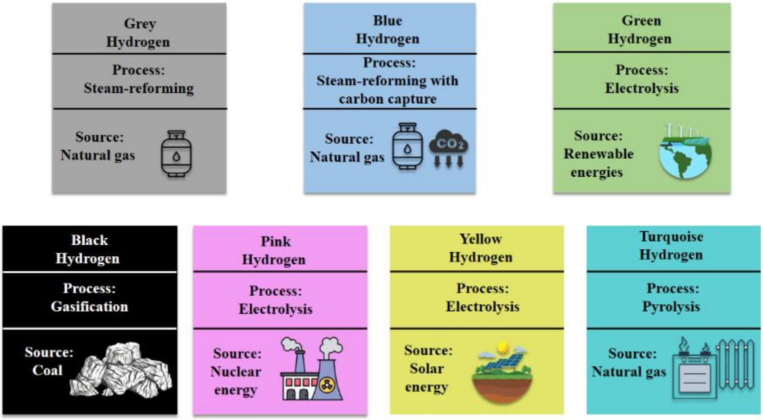

Figure 1: *Different types of hydrogen based on production methods and energy sources, from fossil-based (grey, blue, black) to renewable-powered (green, yellow, pink) and emerging methods like turquoise hydrogen.*

1.4. Methods of Green Hydrogen Production

1.4.1. Electrolysis process

Electrolysis is the technique of using electricity to separate water molecules to produce hydrogen and oxygen.

$$H_2O+Electricity \rightarrow H_2+0.5O_2 \quad (6)$$

Electrolysis of water is an old technology that has served in many industries for over a hundred years. The process of splitting water and hydrogen by water electrolysis using electrical energy. The amount of energy needed to generate hydrogen grows to a certain degree as the electricity needed in the process reduces with an increase in temperature. It is, however, more crucial due to the fact that the majority of power generated on this planet is achieved at very low efficiency through fossil fuels. It is now viewed as a significant process that can be implemented to generate high-purity hydrogen with the use of both water and renewable energy. Shortly, a larger role is foreseen for water electrolysers in decentralised hydrogen production, e.g., at hydrogen refuelling stations. As Figure 2 shows that electrolysis, a strategic approach that has been developed and portrays relevance, is the best method through which water can be split. It also involves the production of hydrogen through a reaction of any of the above substances with water. Proton exchange membrane, alkaline, and solid oxide electrolysis cells are used to perform electrolysis. Water might easily be split into hydroxide particles and hydrogen at the cathode end in solid oxide electrolysis cells and under alkaline conditions. On the anode end, the hydroxide particles are changed to O_2. The electrolyser that is recommended is called the solid oxide electrolysis cells, which use less electricity due to the increase in temperature in the intermediate cycles. With regard to the overall production and consumption of electricity, this warming causes improved electrolysis.

1.4.2. Solar-powered electrolysis

Solar-powered electrolysis Solar-powered electrolysis is a clean technology, which entails the electrochemical separation of water into hydrogen and oxygen utilising electric energy obtained from solar power. The sunlight is normally converted into electrical energy by photovoltaic solar panels, and this energy is used to power an electrolyser, usually a proton exchange membrane (PEM) model, which is highly efficient and quick to respond to changes in power input. The above systems lack efficiency due to the average efficiency of the solar panels (18-22%) as well as the energy efficiency of the electrolyser (60-80%). During the peak sunlight, a 1 kW solar system can produce approximately 0.076 kilograms of hydrogen daily, and this adds to approximately 27.7 kilograms a year in propitious circumstances. This method of green hydrogen generation significantly reduces the level of CO_2 pollution as compared to the conventional fossil-fuel-driven method of producing hydrogen. However, due to the fact that the level of solar energy does not always remain the same throughout the day, hydrogen production also fluctuates, and that is why energy storage, or a hybrid system, is needed to provide a constant supply of it. To conclude, the solar-powered electrolysis of water is a potentially successful line of clean hydrogen production, as the world is on the verge of shifting to renewable energy and decarbonization.

1.4.3. Green hydrogen production method

The solar-powered electrolysis method entails the use of solar energy to produce the electricity required to accomplish the electrolysis of water. Firstly, PV solar panels absorb sunlight and turn it into direct current (DC) power. This power is next delivered to an electrolyser, most usually a proton exchange membrane (PEM) or alkaline electrolyser, in which water molecules are broken into hydrogen and oxygen gases. In the electrolyser, an electric current is induced to flow through the water, and this causes the hydrogen to be separated towards the cathode, where the hydrogen ion obtains electrons to form hydrogen gas; the oxygen will be set free at the anode. It is an extremely controlled operation, as efficient as possible, and tends to come with power management systems in order to handle the on-demand power production of the sun, based on the strength of the sun's rays. Hydrogen gas so produced can be captured, stored, and utilised as a clean source of energy. This technique allows renewable, carbon-free production of hydrogen by the direct combination of solar electricity and water electrolysis.

1.4.4. Wind-powered electrolysis

Wind-powered electrolysis is a technique to harness wind power and apply it to electrolysis of water, using the electricity generated to separate water into hydrogen and oxygen. Wind turbines in this process extract the kinetic energy of the wind and turn it into electrical energy, typically alternating current (AC). This electricity may be used directly or may be modified to the form of direct current (DC) to power an electrolyser, e.g., a proton exchange membrane (PEM) or alkaline electrolyser. In an electrolyser, the electricity flows through it, in which the water molecules (H_2O) are split into hydrogen gas at the cathode and oxygen gas at the anode. The generated hydrogen can be captured, stored, and utilised as a clean fuel in diverse activities, such as transportation, industry processes, and electric power production. Wind-powered electrolysis provides a renewable and green alternative to produce green hydrogen since wind energy is renewable and has no greenhouse gas emissions. However, due to the variable wind speed, storage of energy or connection to the grid is frequently considered to stabilise the production of hydrogen.

1.4.5. Biological methods

Biological hydrogen production is a category of renewable processes, whereby living organisms, primarily microorganisms such as bacteria, algae, and cyanobacteria, are used to produce hydrogen gas (H_2) as a by-product of their natural metabolic processes. These biological systems depend on enzymes like hydrogenase and nitrogenase that facilitate the generation of hydrogen according to the environmental setting. The exceptional benefit of this strategy is that it can use low-value resources, including agricultural waste, wastewater, and sunlight, to create hydrogen in a carbon-neutral or even carbon-negative way. This renders it extremely viable in terms of sustainability compared to the conventional approaches, such as steam methane reforming, that release large volumes of CO_2. Biological hydrogen production can be seen within the context of the whole biohydrogen technology, which is a sub-discipline of green energy technology that is focused on creating inherently clean, decentralised, and low-cost sources of hydrogen, particularly applicable to rural or resource-constrained regions. Although in the early phases of industrial application, the technology is becoming interesting owing to its environmental advantage, and the current drive towards clean hydrogen economies across the world.

1.4.6. Thermochemical method for green hydrogen production

Thermochemical processes involve the production of hydrogen by driving high-temperature chemical reactions with heat typically supplied using renewable resources such as concentrated solar power, geothermal energy, or the combustion of biomass. They are usually done by decomposing water or other compounds that contain hydrogen using heat reactions without the use of electricity. As an example, in thermochemical water splitting cycles, heat is used to continuously promote a sequence of chemical processes that eventually split water into hydrogen and oxygen. Thermochemical methods hold potential to be a low-greenhouse-gas-emission route to clean, sustainable hydrogen, with the key distinction of using renewable heat as a feedstock rather than fossil fuels. Most of these technologies are, however, still under development and need special materials and temperature control to be effective.

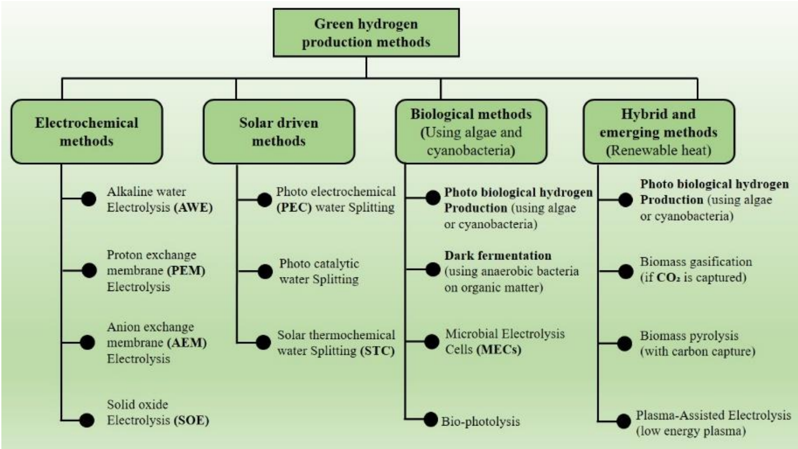

Figure 2: *A structured overview of green hydrogen production pathways, showcasing advanced electrochemical, solar-driven, biological, and hybrid technologies focused on sustainability and renewable energy integration.*

1.5. Challenges and Opportunities

1.5.1. Cost and Efficiency

Cost reduction and efficiency are one of the largest obstacles in hydrogen production and green hydrogen in particular. As of 2022, green hydrogen generated through electrolysis has a cost of between 4 to 6 US dollars per kilogram, making it much more expensive than hydrogen generated by fossil fuels (about 1 to 2 US dollars per kilogram using steam methane reforming). To make hydrogen competitive, it is important to improve the efficiency of electrolysers, reduce the expense of renewable power, and develop catalyst and membrane materials. Research is expected to enhance electrolyser efficiencies to exceed 70 percent and cut capital costs in half by 2030. Figure 3 shows a modern Sankey diagram of the pathways of hydrogen production in 2025.

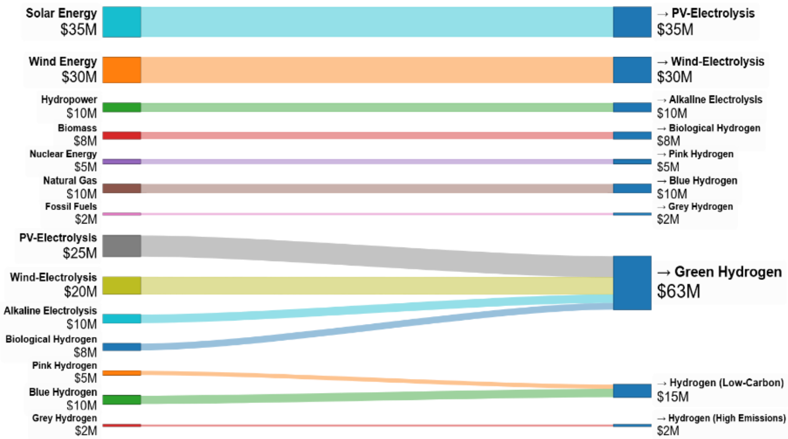

Figure 3: *Renewable and non-renewable sources of energy, through the main conversion processes, to the end uses of hydrogen in industry, transport and power*.

1.5.2. Scalability

The potential of green hydrogen to be produced on a large scale is enormous and can serve energy needs in the future. In order to provide an example, the International Energy Agency (IEA) suggests that global demand for hydrogen could extend to over 500 million tons by 2050, as opposed to the current requirement of 90 million tons in 2020. The opportunities include scaling up manufacturing capacity and facilities, integrating renewable energy sources, and scaling up large-capacity electrolyser plants. Most countries have revealed some ambitious goals, such as the European Union, which hopes to possess 40 GW of renewable hydrogen electrolysers by 2030.

1.5.3. Infrastructure

The challenges are of building an extensive hydrogen production, storage, as well as transportation infrastructure. Low energy density, low molecular size of hydrogen would also require special high-pressure tanks, pipes, and precautionary measures. At present, hydrogen infrastructure is not extensive, e.g., there are currently 500 hydrogen refuelling stations globally, predominantly in Japan, Europe, and California. The infrastructure will have to be expanded, which will need significant investments estimated in hundreds of billions of dollars worldwide over the next 20 years, to allow broad applications in industries, transport, and power generation. Figure 4 shows the low usage of low-emission hydrogen sources.

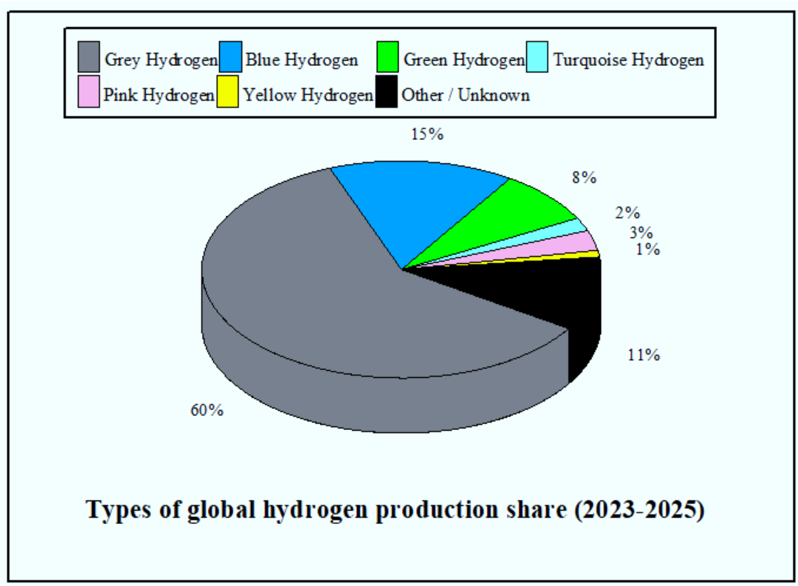

Figure 4: *Worldwide hydrogen capacity (2023-2025) is dominated by grey hydrogen (60%), followed by blue (15%), green (8%), and other colours such as pink, yellow, and turquoise.*

1.6. Conclusion

Hydrogen is a new, clean, and flexible energy carrier whose importance has been re-engineered by the ultimate transition to a low-carbon and sustainable energy future in the world. The contrast of hydrogen in various colours, namely, hydrogen grey, blue, turquoise, and green, defines the difference in the impact that the various production routes have on the environment. Green hydrogen that is produced using renewable sources of energy, including wind and solar, through the process of electrolysis, emerges as the most viable and eco-friendly option amongst the rest. It provides a zero-emission route to decarbonization of hard-to-electrify sectors, such as heavy industry, long-haul transportation, and grid energy storage. This potential fits right into the ambitions of the international climate policies and net-zero pledges. To sum up, green hydrogen has the potential to transform energy systems in the world, yet achieving this promise requires intense action in technology innovation, infrastructure building, and policy reinforcement. Research investments in improving the efficiency of electrolysers, dropping production costs, and increasing the scaling of renewable energy integration are essential. At the same time, global cooperation on standards, safety measures, and market structures will also be needed to realise the successful implementation of hydrogen technologies. With the world racing towards a decarbonised future, green hydrogen is expected to be at the centre of developing a clean, resilient, and inclusive energy landscape.

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