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Review

The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production

Jose M. Marín Arcos and Diogo M. F. Santos *

Center of Physics and Engineering of Advanced Materials (CeFEMA), Laboratory for Physics of Materials and Emerging Technologies (LaPMET), Chemical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal

* Correspondence: diogosantos@tecnico.ulisboa.pt

Abstract: Hydrogen has become the most promising energy carrier for the future. The spotlight is now on green hydrogen, produced with water electrolysis powered exclusively by renewable energy sources. However, several other technologies and sources are available or under development to satisfy the current and future hydrogen demand. In fact, hydrogen production involves different resources and energy loads, depending on the production method used. Therefore, the industry has tried to set a classification code for this energy carrier. This is done by using colors that reflect the hydrogen production method, the resources consumed to produce the required energy, and the number of emissions generated during the process. Depending on the reviewed literature, some colors have slightly different definitions, thus making the classifications imprecise. Therefore, this techno-economic analysis clarifies the meaning of each hydrogen color by systematically reviewing their production methods, consumed energy sources, and generated emissions. Then, an economic assessment compares the costs of the various hydrogen colors and examines the most feasible ones and their potential evolution. The scientific community and industry's clear understanding of the advantages and drawbacks of each element of the hydrogen color spectrum is an essential step toward reaching a sustainable hydrogen economy.

Keywords: hydrogen production technologies; hydrogen colors; techno-economic analysis

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1. Introduction

Times are changing quickly in the energy industry. Climate change has become a real threat, and it is impossible to keep supplying energy from the same polluting sources for much longer. Fossil fuel consumption needs to be gradually decreased to avoid further and irreversible climatic consequences. Several clean energy sources have been evolving over the past two decades, such as solar, wind, and other renewable energy sources. As these energy sources start overcoming the old polluting ones, new challenges with the need to be solved appear. One of the main existing problems caused by this energy transition is related to energy storage.

Matching energy production from renewable sources with the population's energy demand is a complex issue. Some resources, such as wind or solar power, are not under control, resulting in fluctuating production. Moments of high energy demand but low production can only be solved by supplying that energy from storage solutions. One of the most common storage solutions used in our everyday life is batteries. A battery is a device that stores chemical energy and converts it to electrical energy. Batteries are suitable for many applications and have been demonstrated to work successfully, ensuring safety and efficiency. However, batteries also present several constraints. The huge demand for batteries leads to massive production, resulting in thousands of batteries being produced daily. Due to the lack of an existing recycling system, most of these batteries will end up as residues in a few years. In addition, some materials used to manufacture batteries are difficult to find and require mining techniques, meaning that someday it will become impossible to maintain this production level.

Hydrogen is another potential storage solution under development and could satisfy several applications. Hydrogen is considered to be an energy carrier, which allows for transporting energy in a usable way from one place to another. It has the highest energy content of any standard fuel by weight. It is important to remark that one kilogram of hydrogen carries about 33 kWh of energy, about three times more than gasoline. Still, at atmospheric pressure, it has the lowest energy content by volume, nearly four times less than that of gasoline.

Hydrogen has the advantage of being clean, non-polluting, storable, flexible, and renewable. It could be considered the "ultimate energy" of the 21st century. It is used in several fields, which include construction, industry, electricity, and transportation. Hydrogen occurs naturally on Earth in compound form with other elements in gases, liquids, and solids. It can be combined with oxygen, which results in water, or with carbon, to form different compounds, such as the hydrocarbons present in natural gas, coal, or petroleum. Consequently, hydrogen must be separated from the other elements to be consumed alone. Of course, it takes more energy to produce and purify hydrogen than what it delivers when converted to useful energy.

Different production methods can be found, depending on the original hydrogen source (e.g., water, natural gas, coal, petroleum). Some production methods are still under research. The most common production methods are steam methane reforming (SMR), which accounts for most commercially produced hydrogen, and electrolysis, which currently stands for less than 4% of the total hydrogen production. These methods will be explained in detail later on. As is known, hydrogen is a colorless gas, but there are around nine colors for identifying hydrogen. These colors refer to the process used to produce the hydrogen, the assessment of the production method, the resources consumed to obtain the required energy, and the amount of polluting emissions generated. The colors that identify these factors are green, grey, brown or black, blue, aqua, turquoise, purple, pink, red, yellow, and white.

This review paper analyzes the different types/colors of hydrogen to establish a technical and economic comparison between them and to understand how feasible these technologies are today. Other challenges regarding hydrogen features could be approached, such as storage techniques or viable applications, but that is out of the scope of this paper.

2. Types of Hydrogen

As mentioned, hydrogen can be produced using different primary energy sources. Thus, these technologies are classified into different colors depending on the production process, the kind of used energy, the hydrogen costs, and the related emissions. The different colors are green, blue, aqua, and white, called low-carbon hydrogen, and then grey, brown or black, yellow, turquoise, purple or pink, and red.

2.1. Green Hydrogen

Green hydrogen, which is also often called "clean hydrogen", "renewable hydrogen", or "low-carbon hydrogen", is, by definition, the hydrogen produced with water electrolysis using electricity from renewable energy sources. By using renewable energy, green hydrogen production does not generate carbon dioxide (CO_2) emissions at any point. This kind of hydrogen is particularly interesting in the energy transition towards a more sustainable energy and transport system.

Nowadays, green hydrogen only represents a tiny percentage of the total hydrogen production because of the high costs involved in its process. However, it has an excellent projection towards the future, being the cleanest type of hydrogen, which will help to satisfy net-zero carbon plans. The following years will determine whether this technology evolves into a feasible option or not.

2.1.1. Production Methods

Electrolysis of Water

Water electrolysis is currently a mature technology applied in several industrial applications. The main advantage of this method is that the used electricity has the potential to be generated with renewable energy that can come from low-carbon or even carbon-free methods [1]. Thus, this technology is seen as the most promising green hydrogen production method, assuming the electrical energy used to power the water electrolyzer comes exclusively from renewable energy sources.

The process of hydrogen production from water electrolysis depends on two half-reactions: the cathodic hydrogen evolution reaction (HER) and the anodic oxygen evolution reaction (OER). Currently, this technology includes four main approaches: alkaline water electrolysis (AWE), proton-exchange membrane (PEM) electrolysis, the solid oxide electrolysis cell (SOEC), and anion-exchange membrane (AEM) electrolysis (Figure 1) [1].

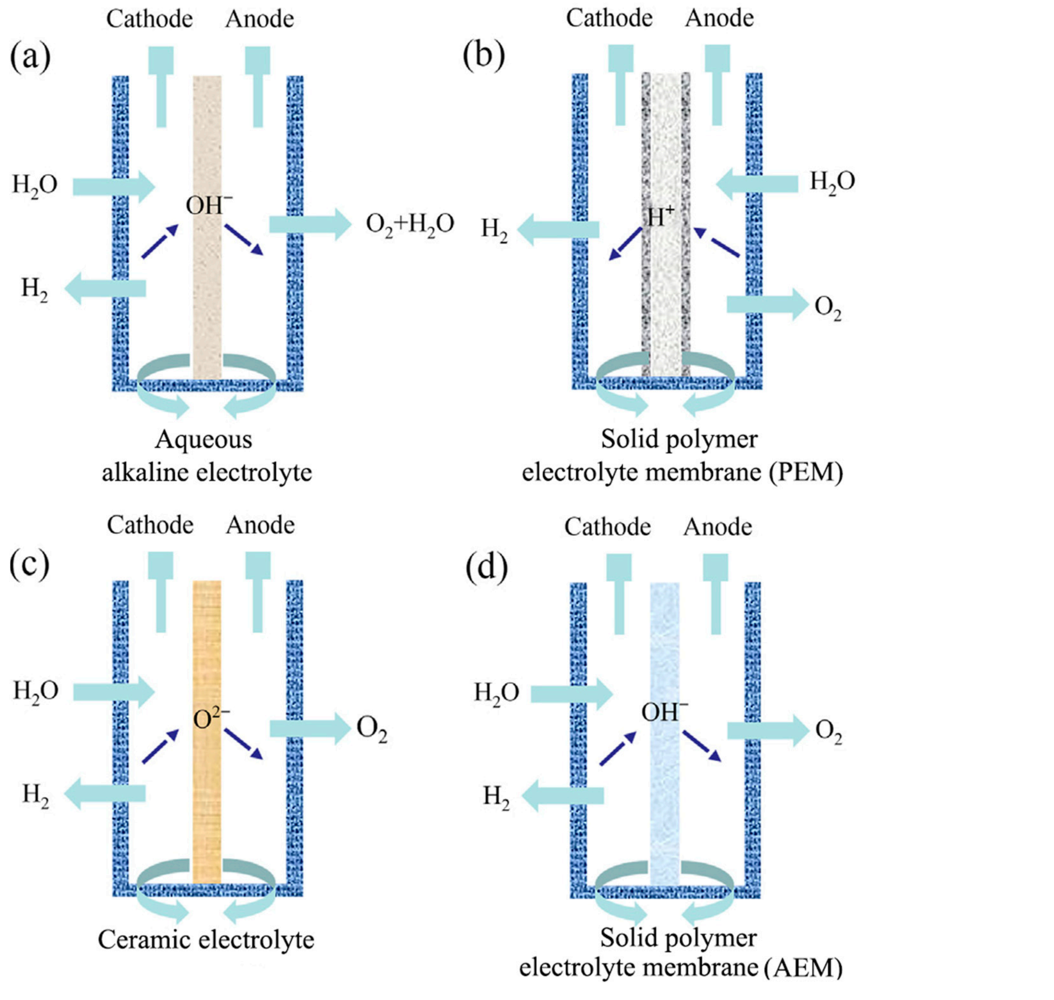

Figure 1. Representation of (**a**) AWE, (**b**) PEM, (**c**) SOEC, and (**d**) AEM electrolysis technologies. Adapted from [1] with permission from Elsevier.

The AWE technology (Figure 1a) belongs to the earliest industrialization time due to its reliability, low cost, and easy operation. Its main drawback is that it occupies a large area. The electrolyzer mainly comprises the electrolyte, diaphragm (generally asbestos), cathode, and anode. In normal conditions, it works at low temperatures, and the pressure between the anode and the cathode must be balanced to avoid an explosion caused by the interpenetration of hydrogen or oxygen. AWE has a relatively long cold start time (ca. 50 min), meaning it starts slowly and requires a long response time [2].

PEM technology (Figure 1b) is easy to integrate and has high conversion efficiency but is very expensive. The catalyst price is one of the main reasons why this technology is not yet applied on a large scale. Still, the small size of the electrolysis cell makes it easier to couple it with wind energy and photovoltaics, which makes it a potential option for the future. The primary device is an electrolytic cell with a polymeric cation-exchange membrane as the core part. There is a bipolar plate that is responsible for connecting multiple membrane–electrode assemblies (MEAs), where the cathode and anode catalysts are deposited over the membrane [3]. Water is fed to the anode side, where its oxidation generates O_2 and H^+, with the latter crossing the PEM membrane to the cathode to form H_2.

SOECs (Figure 1c) use high working temperature conditions and are subjected to many restrictions, requiring a high standard of the used materials [4]. For this technology, the cathode is usually a nickel-based porous cermet. At the same time, the anode is based on a perovskite oxide containing rare-earth elements, and the ceramic electrolyte is an oxygen ion (O^{2-}) conductor.

AEM electrolysis (Figure 1d) is still in the research stage, with many aspects under development. An anion-exchange membrane capable of good ion conduction at low temperatures is used as the separator [5]. This system is similar to the PEM electrolyzer, with the water being fed to the cathode side instead, and has a fast start-up time.

All these hydrogen production technologies via water electrolysis are continuously under research and innovation seeking to reduce costs and improve efficiency. Depending on the technology, several components are studied and tested, such as the catalysts, the used materials, or the ion-exchange membranes. The water electrolysis process will undoubtedly have a cheaper cost in the future, as this is one of the main goals of accomplishing massive green hydrogen production.

Photocatalysis

Fujishima and Honda discovered in 1972 that photocatalytic water splitting on a TiO_2 electrode could produce hydrogen. Photocatalysis is the process where a catalyst absorbs photons to generate high-energy electrons and holes, followed by a redox reaction, as represented in Figure 2 [6]. This is performed by using a semiconductor photocatalyst to generate an electron–hole pair under the irradiation of light. H_2 can be obtained as the target product in the reduction reaction [1]. With this method, solar energy can be converted or stored as chemical energy, one of the most promising advantages of green hydrogen production. Thus, photocatalytic water splitting is seen as the cleanest way to produce hydrogen, as it only uses sunlight to split water directly into H_2 and O_2.

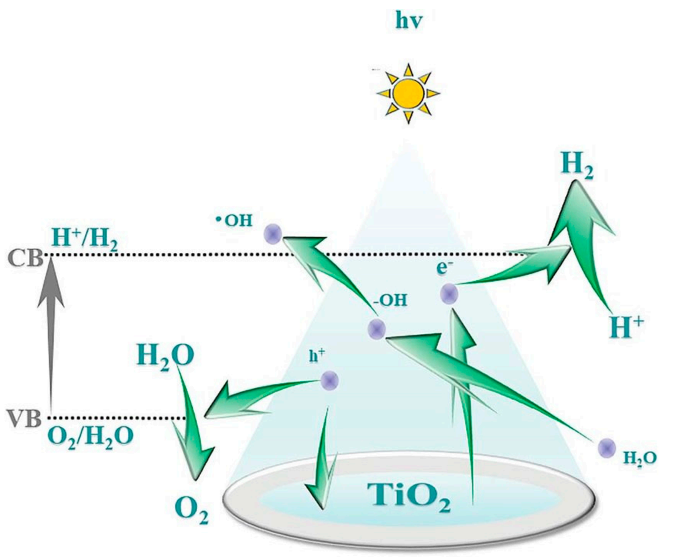

Figure 2. Mechanism of photocatalytic water splitting for hydrogen production [6].

Besides water, other compounds such as alcohols and biomass have been studied as photocatalytic raw materials for H_2 production. One of the keys in the application of photocatalysis is the recombination of photogenerated charge and poor light absorption. Several options are being tested, seeking to improve photocatalytic performance. Considering the low radiation efficiency of the light source, poor reactivity is the main limitation for large-scale commercial applications.

Additionally, the photocatalytic mechanism for hydrogen production is uncertain, with most studies focusing on the energy band and the catalyst. The reasonable design of reactors and devices is also crucial for enhancing catalytic activity, but such research is still limited. As it is a production method that converts photons directly into H_2, it is expected that this technology will evolve into a more efficient one in the coming years, playing a pivotal role in green hydrogen production.

2.1.2. Renewable Energy Sources

Wind Energy

Wind energy is one of the most promising sources for producing green hydrogen. The wind energy is first converted into electricity using wind generators, and the hydrogen is later generated with water electrolysis. Depending on whether the wind generators are connected to the grid or not, they are divided into three types [7]:

- Grid-connected system, where the wind turbines are connected to the grid, thus obtaining the electricity from the grid (100% renewable energy) and producing the hydrogen by electrolyzing water. This method is commonly used for wind consumption and energy storage of large-scale wind sites.
- Off-grid system, where the electricity is generated by single or multiple fans directly connected to the electrolysis equipment, without connecting to the grid. It is often used for distributed hydrogen production systems.
- Grid-connected without transmission, where the turbines are connected to the grid, but the energy is not transmitted to other sites. It only meets local hydrogen production demand.

Solar Energy

Solar energy is the other primary renewable source participating in green hydrogen production. There are two ways to connect the solar energy source with the application [8]:

- A direct coupling system achieves an optimal structure matching between the photovoltaic array and the electrolyzer, using a DC–DC controller and a storage battery. In this case, maximum power point tracking (MPPT) is not included.
- Indirect connection involves the use of photovoltaic and control modules, batteries, and hydrogen storage systems and is the most commonly used method for photovoltaic-water electrolysis hydrogen production systems. As it requires electronic equipment, such as the MPPT and DC–DC controllers, some power transmission losses may occur, dropping the efficiency and increasing the cost.

Other Renewable Energy Sources

The renewable energy sources that currently take the most significant role in green hydrogen production are wind and solar energy. However, other renewable sources produced without any greenhouse gas (GHG) emissions can also be considered, such as hydropower. There are plans to start working with hydro energy as a source for green hydrogen production, which can be seen in a project aiming to prepare hydrogen production maps for regions in Turkey based on the hydro energy potential for use in electrolyzers [9]. In the near future, some other technologies may appear to obtain the greenest energy possible from every kind of renewable energy source.

2.2. Purple (Violet), Pink and Red Hydrogen

According to the literature, pink hydrogen is produced with water electrolysis using electricity from a nuclear power plant. It was also considered that purple hydrogen is obtained by using nuclear power and heat through combined electrolysis and thermochemical water splitting [10]. Red hydrogen is generated through the high-temperature catalytic splitting of water using nuclear thermal power as the energy source. Some may establish that they can be considered the same.

The use of nuclear electricity for hydrogen production is not significantly promoted in the European Union's hydrogen strategies; however, it may be a useful alternative for other regions, such as Russia and China. France is also pushing for this new technology, and attaching a hydrogen production facility can help reduce the curtailment of nuclear plants [11]. Figure 3 shows hydrogen production with different sources of energy [12].

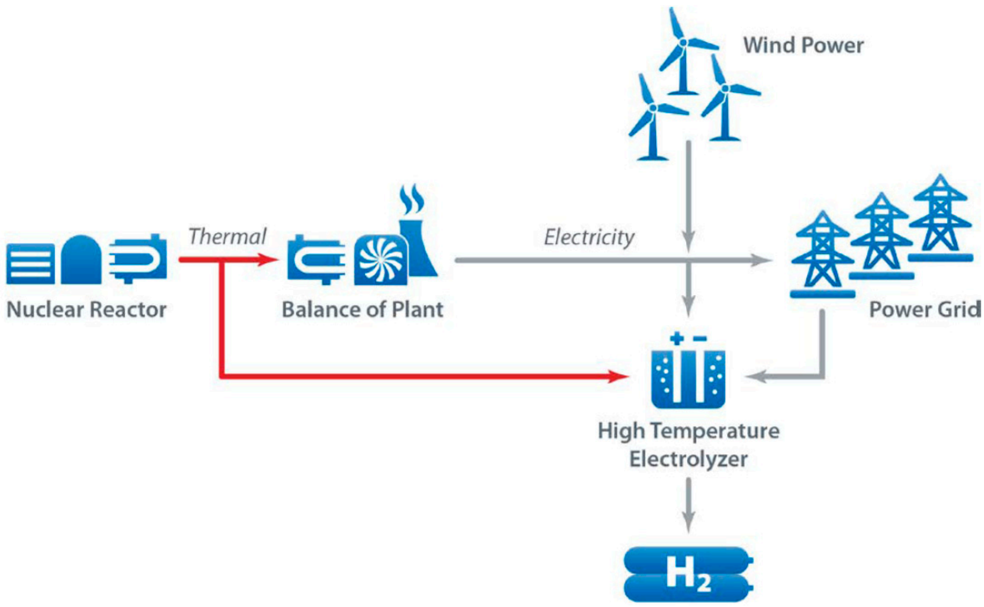

Figure 3. Energy sources for pink, green, and yellow hydrogen production [12].

2.3. Yellow Hydrogen

Yellow hydrogen is produced with electrolysis using electricity from the energy grid. Carbon emissions vary significantly in time, depending on the grid's energy sources [13]. The grid results from the injection of electricity from every power source available. The sources and technologies have changed over time, and some are used more than others, depending on the country.

Using Spain as an example, the electricity generated and fed to the grid during 2021 came from the following power mix. With a share of 23.3%, wind energy was the most commonly used source, followed closely by nuclear power, with nearly 21% of the electricity generation [14]. Later, there was the combined cycle with 17.1% and hydropower generation with 12.4% of the total share, followed by cogeneration at 10% and solar photovoltaic at 8%.

Figure 4 summarizes the power mixes from several countries and regions [15]. Iceland has the greener power mix, with ca. 30% of the energy coming from geothermal and the rest from hydropower. Yellow hydrogen in Iceland would probably be close to green hydrogen, as the energy sources of its power mix are clean sources without emissions.

It is important to mention the chlor-alkali industry as an essential part of the chemical industry. It produces chlorine and sodium hydroxide through the electrolysis of brine, a saturated sodium chloride solution obtained from natural salt deposits [16]. In this process, hydrogen is classified as a byproduct that may be combusted for process heat, sold as a commodity to the external market, or wasted by simply venting it into the atmosphere. Thus, the byproduct hydrogen from the chlor-alkali industry can help meet the market's increasing demand [17]. As the process involves electrolysis and the energy source is typically the grid, it can also be considered yellow hydrogen, even though some sources consider it white hydrogen. Some authors recognize yellow hydrogen as being produced through electrolysis via solar power, although this designation is now becoming obsolete.

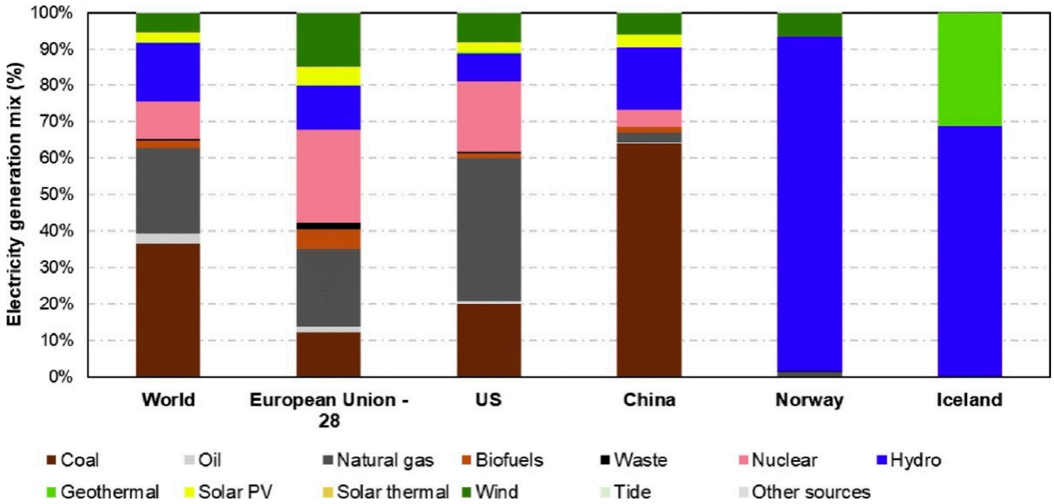

Figure 4. Electricity generation mix in 2020 [15].

2.4. Grey Hydrogen

Grey hydrogen denotes hydrogen produced from steam methane reforming, partial oxidation, or autothermal reforming. Currently, most of the produced hydrogen corresponds to grey hydrogen. It is important to highlight that 40% of grey hydrogen is a byproduct of other chemical processes. Grey hydrogen is generally used in the petrochemical industry and for ammonia production [18].

As seen in Figure 5, the hydrogen demand for these applications increased substantially over the last 50 years [19]. Around 6% of the worldwide extracted natural gas and 2% of coal are used to produce grey hydrogen. The main disadvantage of grey hydrogen is related to the high CO_2 emissions during hydrogen production (ca. 830 Mt CO_2 per year) [20].

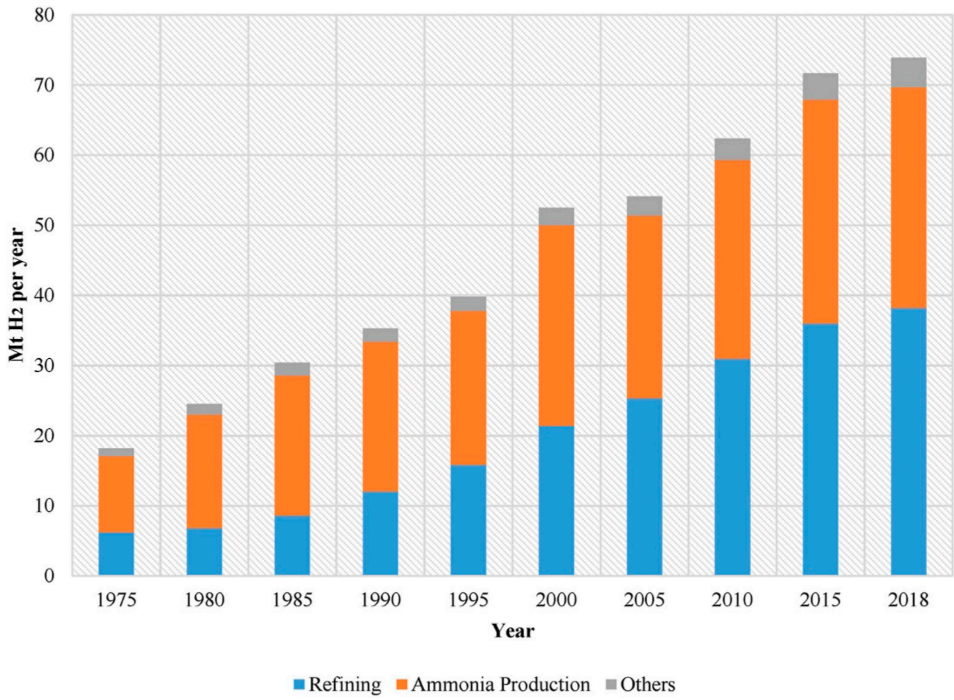

Figure 5. Hydrogen demand for the last 45 years [19]. Reprinted with permission from Elsevier.

2.4.1. Production Methods

Steam Methane Reforming

Steam methane reforming (SMR) is a mature technology that, in combination with the water–gas shift reaction, allows the production of grey hydrogen. It is currently the most common and cost-effective method to produce hydrogen, accounting for 80% of the global demand [21]. Steam reforming was first implemented in the industry in the 1930s in the United States, where methane was highly available. However, it was not until the 1960s that this technique broke into the syngas and methanol industry, with naphtha mainly being used as feedstock across Europe [22]. Natural gas has proven to be the most suitable raw material for steam reforming due to its high availability, ease of transportation, and higher composition homogeneity compared to other fossil fuels. Most of this hydrogen (around 95%) is used as feedstock for ammonia, methanol, and the synthesis of liquid fuels (by Fischer–Tropsch processing) [21].

The steam reforming process involves a reaction between hydrocarbons and steam to produce a mixture of hydrogen and carbon monoxide, known as syngas (Figure 6) [23].This process requires high temperatures and pressures, ranging from 700 °C to 1000 °C, and 5–20 bar, depending on the desired yields, the reactors, and the catalysts employed. With this being an endothermic process with a high-temperature demand, the supply of thermal energy becomes a remarkable aspect. Usually, on a large scale, this supply is provided through fossil fuels. However, some experimental facilities worldwide carry out this reaction by providing heat via concentrated solar power. Some of the most advanced pilot plants can be found in Almeria (Spain), Zurich, Rome, and Colorado. However, high surface areas are required to reach these temperatures and carbon depositions due to the added difficulties in controlling the reactor [24].

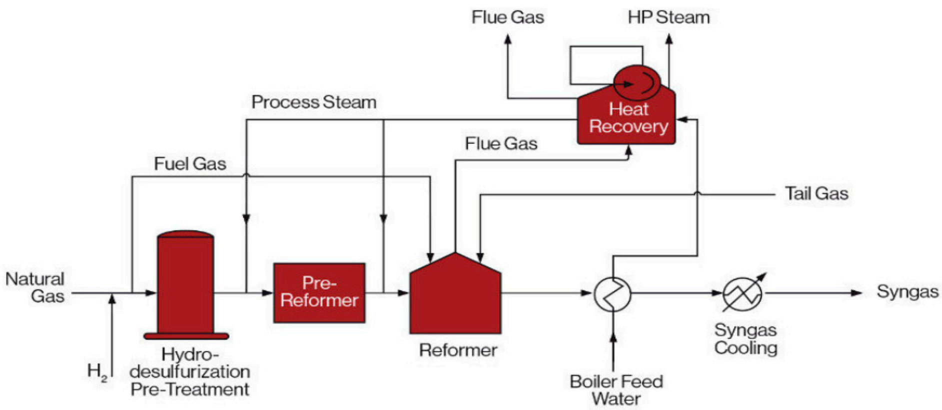

Figure 6. Hydrogen production from steam methane reforming [23].

Partial Oxidation

Partial oxidation is a process where grey hydrogen is obtained from hydrocarbons, typically natural gas. This technology is commercially available and can be considered mature. In this process, the combustion is carried out with a limited amount of oxygen. As a result of the sub-stoichiometric oxygen supply, only partial oxidation of the carbon takes place, so CO is produced instead of CO_2. The other reaction products are hydrogen and nitrogen if the air is used instead of pure oxygen. Due to the high temperatures, using a catalyst is not mandatory. However, the catalyst significantly increases the reaction yield [25].

The partial oxidation process is faster than steam reforming and involves a smaller reactor vessel. A disadvantage is that less hydrogen is produced per input fuel than with the steam reforming process. Finally, the gas stream is cleaned of CO_2 and other impurities [26].

2.5. Turquoise Hydrogen

Turquoise hydrogen also uses methane as the feedstock but is produced via methane pyrolysis. Contrary to SMR, the byproduct is solid carbon appearing as filamentous carbon or carbon nanotubes. This type of byproduct can be further used and is easier to store, thus having a lower carbon footprint [27]. Furthermore, it may be sold for other applications.

The pyrolysis of methane can be carried out through three approaches: thermal decomposition, plasma decomposition (known as the Kvaerner process), and catalytic decomposition. This technique has already been known for decades and is technically performed in several processes. Still, it has recently been considered an interesting option for hydrogen production [28]. So far, pyrolysis has never been commercialized as a hydrogen production method. The thermal process is being further developed with the target of producing hydrogen in large quantities.

2.6. Brown and Black Hydrogen

Considering production from coal, the brown and black hydrogen colors refer to the type of lignite (brown) and bituminous (black) coal. It is regarded as the least environmentally friendly hydrogen production method, creating as much CO_2 as burning the source fuel would have in the first place. Around 20 kg of CO_2 is released for every kg of brown/black hydrogen produced [29]. This is a highly used hydrogen production method, as coal is the fossil energy source with the largest worldwide reserves. Notably, China produces large amounts of hydrogen through coal gasification due to high natural gas prices and large coal reserves [30].

Although some authors claim that hydrogen from biomass gasification should be seen as green, assuming the whole lifecycle of the biomass is carbon-neutral, the undeniable high CO_2 emissions of the process lead most authors to consider it brown hydrogen.

2.6.1. Production Methods

Coal Gasification

Coal gasification is one of the most important hydrogen production methods and can involve different techniques. Gasification is known as the process of converting any carbon-based raw material into syngas using air, steam, or oxygen. Gasification techniques can effectively convert many raw materials and wastes (e.g., coal, car tires, sewage sludge, sawdust, wood, and plastic waste) into valuable outputs. The end product gas of the gasification process can include some (or all) of the following compounds: CO, H_2, CH_4, ash, tar, H_2S, NH_3, HCl, and HCN. Purification of the product gas is then required to remove contaminants, particles, and other substances, thus decreasing its calorific value. This may involve applying several gas clean-up processes to adequately separate the useful gases, such as CO, H_2, and CH_4.

In the gasification process, four types of coal are usually utilized (Figure 7). These are lignite (low rank), sub-bituminous coal (low rank), bituminous coals (medium rank), and anthracites (high rank) [31].

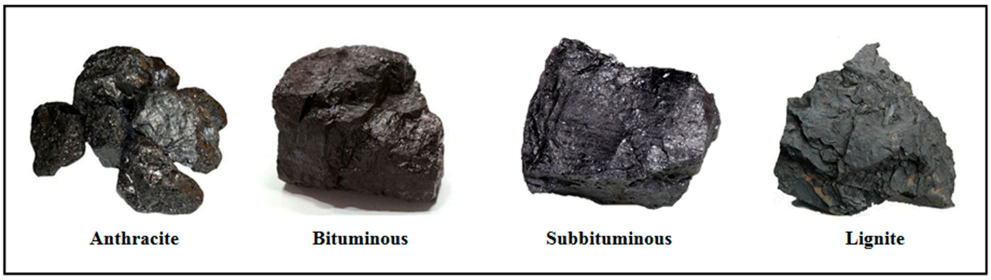

Figure 7. Different types of coal [31].

It should be noted that these materials are generally gasified at temperatures higher than 900 °C by applying fixed bed gasification, moving bed gasification, fluidized bed gasification, entrained flow gasification, or plasma gasification. Particularly, the latter is recognized as a relatively recent technology that uses plasma torches for producing clean and renewable fuels. Some of the listed methods are schematically shown in Figure 8 [32]. Among gasification processes, the entrained and plasma gasification of coal are usually carried out at higher temperatures of ca. 1200 and 1700 °C, respectively, whereas the other processes require operating temperatures lower than 1200 °C [33].

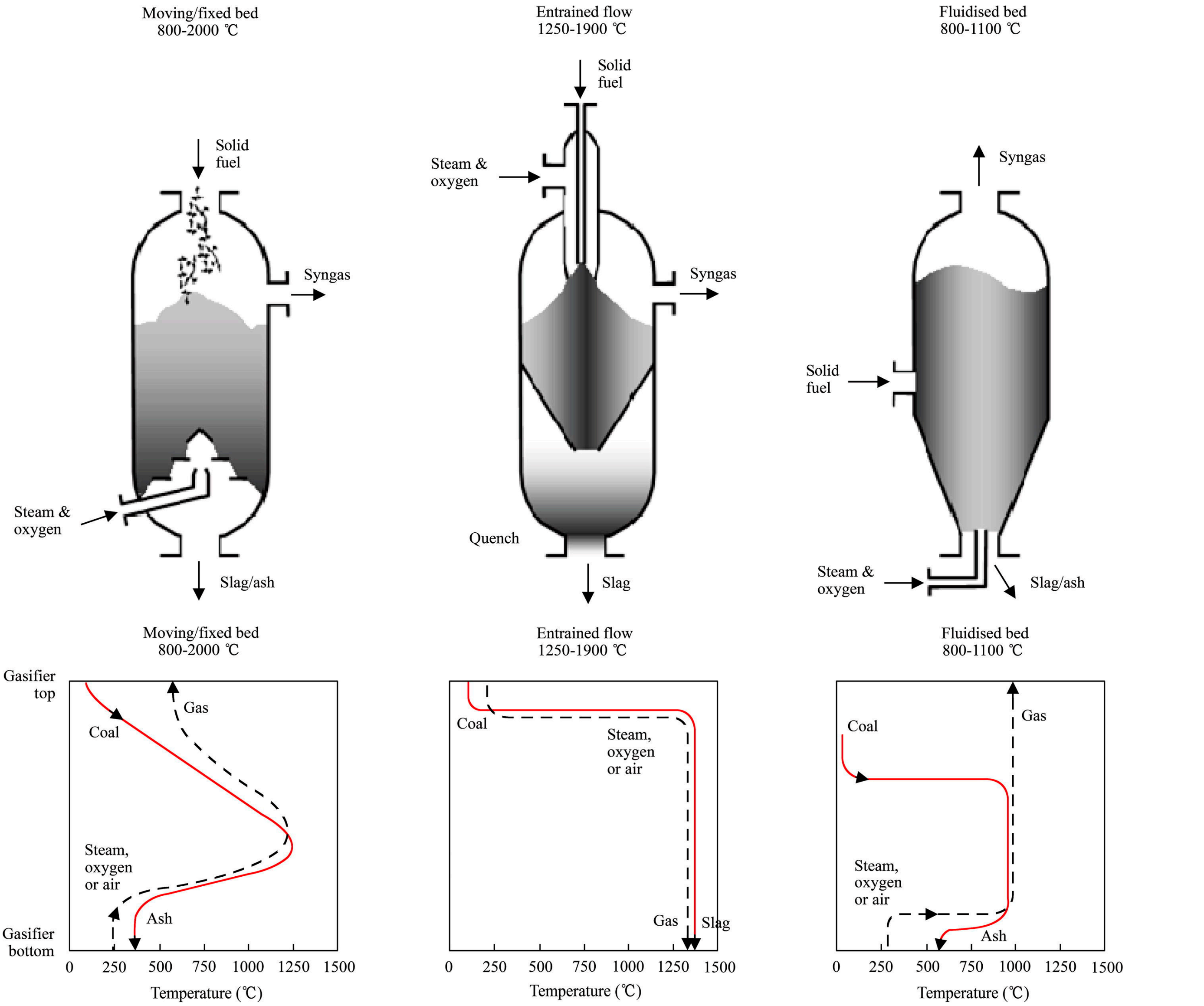

Figure 8. Gasification techniques for brown and black hydrogen production with coal gasification [32].

Coal gasification still seems to be an important process for relatively cleaner and cost-effective production of energy and chemical products. Compared to the traditional coal combustion process, one can point out the following advantages of coal gasification:

- Higher efficiency in the conversion of coal's high moisture and ash content into valuable products.
- Production of high-calorific-value syngas.
- This hydrogen-rich syngas leads to higher-efficiency electricity generation, significantly decreasing carbon emissions.

Co-Gasification of Coal

Researchers have studied the effect of mixing different biomass ratios on the performance of coal gasification. It was demonstrated that the coal gasification rate improved with the amount of biomass in the mixture. Furthermore, hydrogen production increased with the increase in temperature. Studies were conducted to design a combined cycle power plant involving the co-gasification of coal with biomass coupled with a carbon capture and storage (CCS) unit. The hydrogen and electricity generation performance in this integrated process was evaluated using four gasification approaches: 100% coal and 80–20% combinations of coal–sawdust, coal–sewage sludge, coal–meat, and coal–bone meal. The coal–meat and coal–bone meal mixtures exhibited the best results for hydrogen production [34].

The gasification of mixtures of coal with small amounts of meat and bone powder (MBM) in a fluidized bed reactor as an alternative for waste management was also evaluated. The work assessed the influence of bed temperature (800–900 °C), equivalence ratio (0.25–0.35), and MBM ratio in the feed (0.1 wt.%) on the quality of the produced syngas. When using air as a gasifying agent, it was seen that MBM had a minimal effect on the amount of H_2, CO, and CO_2 synthesis gases. The work demonstrated that the hydrogen ratio in the produced syngas increased with the temperature and decreased with the equivalence ratio [34].

Biomass

Using biomass as raw material can be another method used to obtain hydrogen. Biomass gasification, involving conversion, decarbonization, and separation, is a promising approach for obtaining pure hydrogen [35]. At the same time, hydrogen-rich compounds such as methane, methanol, or ethanol can be obtained by other processes, including enzymatic hydrolysis and fermentation. High-purity hydrogen can be reached by reforming these hydrogen compounds through catalytic reactions. These different processes are summarized in Figure 9 [1].

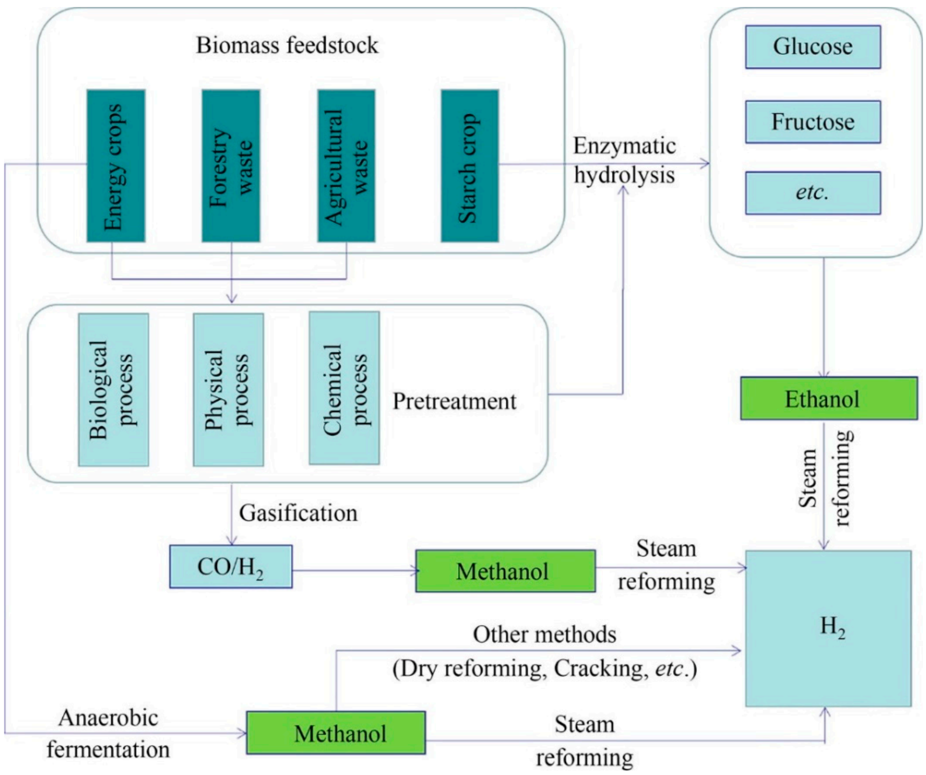

Figure 9. Hydrogen production routes from biomass [1]. Reprinted with permission from Elsevier.

There are two pathways to produce hydrogen from biomass: biological or thermochemical hydrogen production. The biological pathway is performed using hydrogen-producing microorganisms and can involve anaerobic fermentation or photosynthetic routes. Still, the possibility of large-scale production is limited due to its poor yield and stability. The thermochemical method may involve the pyrolysis of the hydrocarbon components of biomass into syngas, followed by the water–gas shift reaction to increase the hydrogen yield [36].

The production of hydrogen from biomass has the basic technological development conditions for industrialization. Even though this process has CO_2 emissions, it can be considered a net-zero carbon emissions process, as the carbon emitted is also incorporated as part of the gasified biomass life cycle. For that reason, a discussion is ongoing on whether this hydrogen should be called green.

2.7. Blue Hydrogen

A very appealing option for low-carbon hydrogen is blue hydrogen. It is based on producing hydrogen from fossil fuels, but with a carbon capture, utilization, and storage (CCUS) system. Utilization is not mandatory to qualify as blue hydrogen. Being produced from fossil fuels, blue hydrogen currently has lower costs than green hydrogen.

As no CO_2 is emitted, the blue hydrogen production process is categorized as carbon-neutral. Blue hydrogen is considered an alternative solution during the energy transition, as it still offers the possibility of consuming fossil fuels, but with a reduction in the carbon footprint. Doing that provides a sustainable vision for some fossil fuel-producing countries (e.g., Canada, Iran, Norway, Qatar, Russia, United States).

Different methods can be used to produce blue hydrogen, some of which are the conventional ones to produce grey, brown, or black hydrogen, although carbon is captured and stored in the former case. There are also several ways of capturing carbon, depending on the stage of the production method. After capturing it, CO_2 can be either utilized for other purposes or transported and stored.

2.7.1. CO_2 Capture

There are several available technologies for carbon capture during hydrogen production at different stages of development and commercialization. The principal CO_2 capture technologies are adsorption, absorption, cryogenic separation, membrane separation, calcium looping, chemical looping, and direct separation calcination technology. Carbon capture technologies can be divided into pre-combustion, post-combustion, and oxyfuel combustion, as shown in Figure 10 [37].

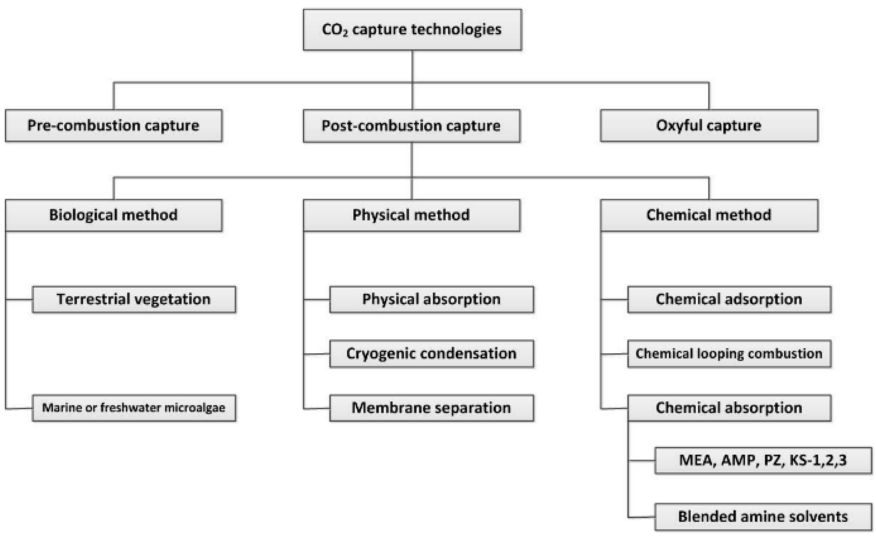

Figure 10. Technology options for CO_2 capture [37].

Pre-Combustion

Pre-combustion carbon capture is the process of CO_2 removal from fossil fuels before combustion is completed [38]. Pre-combustion technology is the most adopted since it is a terminal technology that can be easily incorporated into any existing system.

Post-Combustion

Post-combustion capture denotes CO_2 removal from fossil fuels after combustion is completed. Among the available technologies, the most suited for pre-combustion capture are physical absorption, pressure-swing adsorption (PSA), and membrane separation [39]. Post-combustion CO_2 capture can be schematically divided into three blocks: biological, physical, and chemical methods. The biological method refers to the photosynthesis of plants, algae (terrestrial but also marine or freshwater microalgae), and photosynthetic bacteria without energy consumption.

Oxyfuel Combustion

Oxyfuel combustion processes use nearly pure oxygen instead of air for the combustion of fuel [40]. The combustion produces an exhaust gas mainly made up of vapor H_2O and CO_2 that can be easily processed through dehydration to obtain a high-purity CO_2 stream [41]. Generally, oxyfuel combustion provokes the recirculation of flue gas to obtain a lower flame temperature, promoting it as a highly efficient combustion technology in terms of energy saving [42]. The salient features can be summarized as follows:

- Pure oxygen replaces air during fuel combustion to obtain high CO_2 concentrations.
- Some of the flue gas must be recirculated to control the temperature of the furnace flame and preserve pertinent heat transfer characteristics.
- Beneficial for CO_2 capture and subsequent compression.

One technology developed that has gained interest is the ion-transport membrane technology, which could considerably contribute to improving the performance efficiency of oxyfuel combustion and the integration of carbon capture in integrated gasification combined cycle systems [39].

As of today, SMR satisfies most of the hydrogen demand thanks to its low cost and high efficiency. Indeed, 9 kg of CO_2 is generated for every kg of H_2 produced. Figure 11 schematically represents the operations of a modern SMR hydrogen plant fed by natural gas [43]. Of the total CO_2 production, approximately 60% is produced in the water–gas shift reactor and PSA tail gas. In comparison, the remaining 40% comes from the combustion of additional fuel gas (non-renewable) required by the steam reformer [43]. CO_2 can be captured from any of the three streams (Figure 11), with a removal efficiency of about 90% from PSA tail gas and steam reforming flue gas, and over 99% from raw H_2.

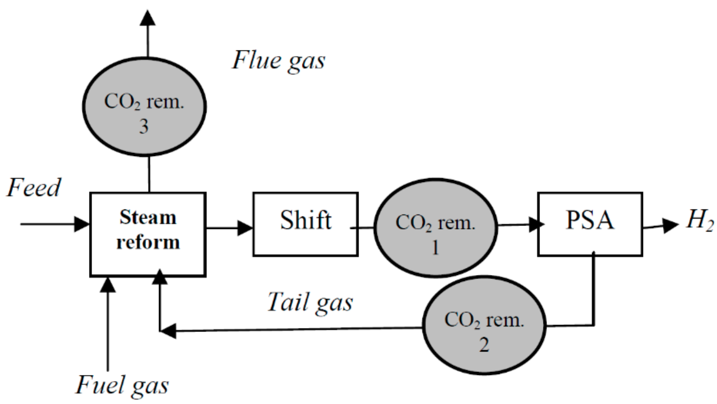

Figure 11. Scheme of a modern steam methane reforming H_2 plant with CO_2 removal [43].

2.8. Aqua Hydrogen

Canada is a major producer of hydrogen from natural gas through SMR, thus producing vast amounts of GHG emissions. The University of Calgary and the company "Proton Technologies" (based in Western Canada) have developed a carbon emission-free technology that allows for extracting hydrogen from oil sands (natural bitumen) and conventional oil fields [44]. This hydrogen can be a zero-carbon approach to enhancing energy recovery from Canada's oil and gas resources.

The aqua hydrogen technology involves placing oxygen into a sealed fuel deposit between grains of rock, using unswept petroleum as the fuel and the ground as the reactor vessel [45]. The process starts by separating atmospheric air into nitrogen and oxygen using air separation units. The oxygen is then sent to an underground reservoir, where the temperature is increased, promoting water–gas shift, hot gasification, and aqua thermolysis reactions within the fuel reservoir, thus generating syngas.

Lastly, the H_2 is extracted using membranes in the production wells. These membranes are composed of a palladium alloy, where carbon oxides stay underground and H_2 reacts with palladium [45]. The process has high efficiency because all energy conversion takes place underground. This technology may be a clean way to generate hydrogen using economically unrecoverable oil reserves, bringing only hydrogen to the surface.

2.9. White Hydrogen

White hydrogen refers to naturally occurring hydrogen. It is found in nature as a free gas in layers of the continental crust, deep in the oceanic crust, or in volcanic gases, geysers, and hydrothermal systems. It seems to be present in a wide range of rock formations and geological regions.

The processes involved in natural hydrogen formation are not well understood. Some hypotheses are hydrogen degassing from the Earth's core, water reacting with ultrabasic rocks (i.e., serpentinization) or with reducing agents in the mantle, natural radiolysis (i.e., water dissociation by uranium or plutonium), and decomposition of organic matter. Some of this hydrogen has been found in New Caledonia. It is believed to have been formed by serpentinization, with the water reacting with local rocks (ophiolites) and releasing hydrogen.

As is known, steam reforming produces grey hydrogen with high efficiency and low cost, but also with a catastrophic carbon footprint. As for electrolysis, it generates green hydrogen from renewable energy sources but loses almost 70% of the energy input throughout the process. Naturally formed white hydrogen appears as a promising carbon-free and abundant source that requires minimal infrastructure for its exploitation [46]. Due to a low level of research on the topic, it is still difficult to assess worldwide white hydrogen resources. The EarthH_2 initiative has been assisting the scientific community and industry in gathering forces and increasing the knowledge on white hydrogen. A hydrogen economy based on white and green may be the answer for the transition to a carbon-free society, enabling a brighter tomorrow for planet Earth and humankind. As mentioned before, other sources may consider hydrogen produced as a byproduct of chemical processes to also be referred to as white hydrogen [47].

3. Economic Assessment

Each color of hydrogen has respectively different costs to take into account. The cost of hydrogen production can rise or decrease depending on the production method, the fuel consumed (e.g., methane, coal, water, electricity), and other factors such as fees (e.g., carbon taxes). Another main factor that should be considered is the geographical location of the facility producing the hydrogen. This section aims to analyze these costs and compare them to establish the most feasible colors of hydrogen. This comparison is made by using the levelized cost of hydrogen (LCOH).

3.1. Levelized Cost of Hydrogen (LCOH)

The LCOH is a methodology used to account for all of the capital (CAPEX) and operating (OPEX) costs of producing hydrogen, enabling the comparison on an equal basis of different production routes. This methodology computes the cost, normally in USD, per kilogram of H_2 produced, i.e., USD/kgH_2. This is the same type of methodology applied to electricity production or energy storage. It is important to emphasize that the LCOH does not include H_2 storage and transport costs that may be necessary depending on the application. Using the LCOH allows for comparing the different hydrogen colors on a similar basis. Figure 12 summarizes the main hydrogen colors next to their production method, whose costs will be analyzed in the following section [48].

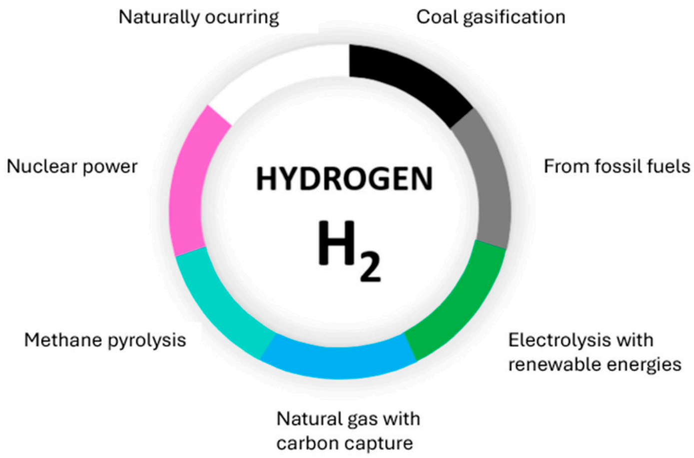

Figure 12. Main hydrogen colors with their respective production methods [48].

3.2. Cost of Hydrogen Production by Color

A careful literature review, including scientific research papers and official documents updated to the present day, has been carried out to estimate the costs for the respective hydrogen colors. Thus, for each color, the estimation was performed by analyzing the different reported numbers and stating the average cost values depending on its geolocation, focusing mainly on developed countries where these practices can be found.

3.2.1. Cost of Green Hydrogen

Many factors influence the cost of green hydrogen. The first one is the cost of electrolysis, the process used for producing hydrogen from water using renewables. Currently, the total capacity of global electrolysis is limited. The electrolyzer assembly and operation involve considerably high production costs and large energy requirements [49].

The second factor is the price of the green electricity used to power the electrolysis process. Electricity cost is the main operating cost of green hydrogen production. By reducing this cost and improving the current technologies that produce this electricity and its efficiencies, green hydrogen will become a feasible and cheap option [50]. Scaling up wind and solar power generation is vital to lower the costs of renewable electricity, which will be crucial for the large-scale production of green hydrogen.

Green hydrogen production through wind power is still an expensive option due to the high capital costs of wind infrastructures. The available wind resources depend on the weather conditions, namely the wind speed, direction, temperature, and air pressure. This uncertainty of wind power significantly affects the green hydrogen cost [51]. As for solar energy, it is the most long-lasting and abundant energy source, but its intermittent character is a complicated problem. The additional component requirements further increase the generated hydrogen cost [52].

The costs of green hydrogen depend on several factors, such as the location (easy/difficult access to green electricity), the production method (e.g., AWE, PEM, SOEC, AEM, photocatalysis), or the capacity and lifetime of the facility. The current cost range of green hydrogen is about USD 2.28–USD 7.39/kgH_2 produced [45]. Of course, the cost may be lowered by increasing the scale of green hydrogen production. To decrease the high cost of the electrolysis process, it is necessary to find ideal materials to produce electrolytic cells and establish a large-scale electrolysis supply chain.

Another key measure to reduce the price of green electricity could be to rely on government policy support and offer financial incentives to stimulate the large-scale progress of renewable energy plants. This should involve solar energy and offshore and onshore wind energy to increase the utilization rate of power generation and decrease green electricity prices. The lack of CO_2 emissions is the best incentive for the industry to invest in it. Even so, it is expected that green hydrogen costs will not be low enough until the 2030s.

3.2.2. Cost of Purple (Violet), Pink, and Red Hydrogen

As previously mentioned, purple (violet), pink, and red hydrogen production are conducted via water electrolysis or a thermochemical process using electricity from a nuclear power plant. Nuclear power already produces electricity as a major energy carrier with well-known applications. The costs of this process are similar to those of green hydrogen, except for the electricity cost. Electricity or heat from nuclear power is cheaper than electricity from green sources; thus, the hydrogen price is lower than green hydrogen.

The cost also depends on the technology used in the hydrogen production process. Table 1 summarizes some features and the hydrogen cost range for nuclear hybrid energy systems, depending on technology [53]. Solid oxide electrolysis seems the cheapest method, even though it consumes the biggest amount of water, followed by the thermochemical process, the PEM electrolysis, and finally, the alkaline electrolysis [53].

Table 1. Hydrogen production costs for nuclear hybrid energy systems [53]. Reprinted with permission from Elsevier.

	Alkaline Electrolysis	PEM Electrolysis	Solid Oxide Electrolysis	Thermochemical S-I
Temperature (°C)	60	60	800	910
H_2 yield efficiency (HHV, %) *	30	27	36	25
Electricity (MJ)	180	200	146	75
Heat (MJ)	26	26	30	375
Water (kg)	11.5	11.5	83	9
Technology readiness level	9	6-8	5	4
Production cost (USD/kgH_2)	5.92	3.56–5.46	2.24–3.73	2.18–5.65

* assuming 40% heat to electricity conversion.

3.2.3. Cost of Yellow Hydrogen

The procedure to calculate the costs of yellow hydrogen is also very similar to the ones for green hydrogen. As before, the technologies used are the same ones, but the source of energy varies, as represented in Figure 13 [54]. In this case, the electricity used is taken from a power mix, the grid, which could have many different sources, from fossil fuels to renewable energy.

Using electricity from the grid allows hydrogen producers to run at a constant maximum load factor. Consequently, they must pay additional electricity costs associated with transmission and distribution. Another drawback is that, as the source is composed of a power mix, CO_2 emissions are released into the atmosphere. The amount of emissions, as well as the cost of the electricity, will depend on the power mix, which will vary depending on the location of the production plant.

The cost range of yellow hydrogen is USD 6.06–USD 8.81/kgH_2 in the US, while in the EU, the cost ranges from USD 4.83–USD 13.11/kgH_2 [55]. These prices are supposed to decrease through the years, as future energy production will have lower costs.

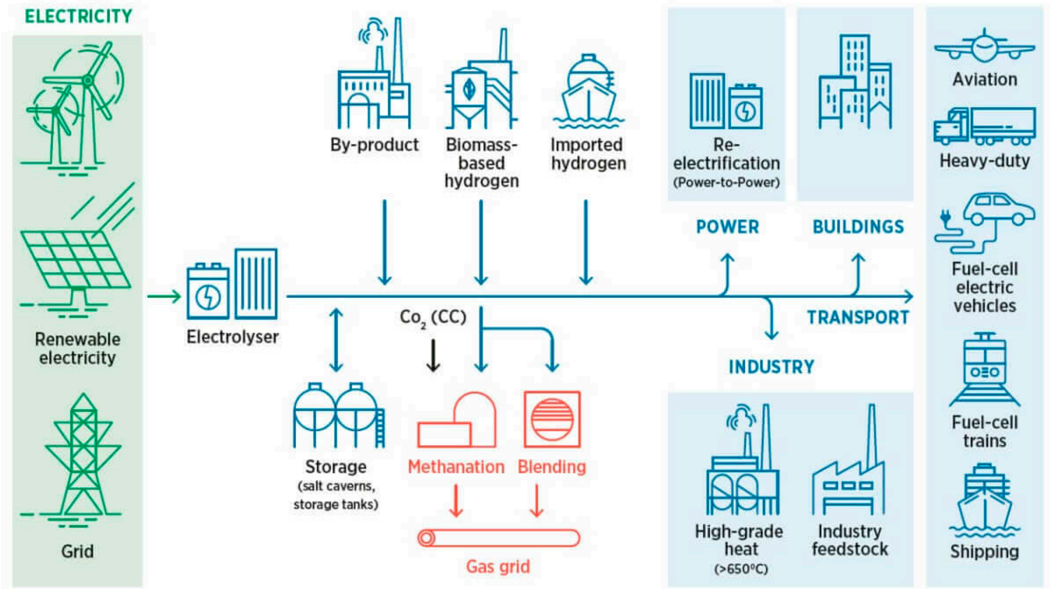

Figure 13. Different hydrogen sources and potential hydrogen applications [54].

3.2.4. Cost of Grey, Black/Brown Hydrogen

The costs of these hydrogen types rely mainly on the price of coal (black/brown) or the price of natural gas (grey). Grey hydrogen can be produced at USD 0.8/kg H_2 in locations with low natural gas prices. According to the International Energy Agency (IEA) [56], the lowest prices for SMR were found in the Middle East, the United States, and Russia, all below USD 1/kgH_2. Europe and China had the highest prices. On the other hand, a big part of the hydrogen produced by China is produced with coal gasification due to its extensive reserves of coal.

The average cost of grey hydrogen is between USD 0.67–USD 1.31/kgH_2. Because of its low cost, most of the current hydrogen is grey. Coal gasification involves higher investment costs than SMR. Thus, black and brown hydrogen have production costs of USD 1.2–USD 2/kgH_2 [56]. Moreover, hydrogen production costs from biomass and waste gasification are somewhat higher, in the USD 1.6–USD 3/kgH_2 range.

Grey, black, and brown hydrogen are the most mature and developed technologies, being the ones used during these last decades as the main source of hydrogen production. These technologies are also much more polluting than all the other hydrogen production methods. For every kg of black hydrogen produced, 20 kg of CO_2 is released into the atmosphere, while grey hydrogen emits around 8.5 kg of CO_2 [45]. For that reason, decreasing the consumption of these fuels is a necessary action toward decarbonization.

3.2.5. Cost of Turquoise Hydrogen

As turquoise hydrogen is produced from methane pyrolysis, it can consume one-seventh of the energy necessary to produce hydrogen from water. Again, the production costs will depend on the price of natural gas, which is the feedstock needed for the pyrolysis process. As mentioned before, this reaction produces a solid carbon byproduct, which can be used afterward for other purposes, such as tire manufacturing. Furthermore, depending on its type, this byproduct can be sold afterward for USD 150–USD 400 per ton of coke, USD 500–USD 1000 per ton of carbon black, USD 1500–USD 1800 per ton of activated carbon, and up to USD 1 million per ton of carbon filaments [57].

For as long as natural gas is available at low prices, turquoise hydrogen can be much less expensive than green hydrogen. There are currently no commercial facilities dedicated to turquoise hydrogen production in operation, but several are under development. The predictable price of turquoise hydrogen is expected to be ca. USD 2/kgH_2, depending on the cost of natural gas [58]. The approximate emissions released when producing 1 kg of H_2 through this process are around 2.6 kg of CO_2.

3.2.6. Cost of Blue Hydrogen

Blue hydrogen is supposed to play a key role in the energy transition, using a CCS system to avoid emissions from being released into the atmosphere. Its price depends on the price of fossil fuels such as coal and natural gas, as for grey, black or brown hydrogen. Furthermore, it is also affected by the costs involved in the process of capturing, reusing, or storing CO_2. The development of blue hydrogen as a solution for large-scale hydrogen production in the energy transition currently faces some challenges: the technology for CCS is still immature, with a high cost and low CO_2 capture efficiency.

Presently, there are a total of 135 CCS projects running worldwide: some operational, others under construction, and some in an early stage [59]. Several CCS projects are currently running among the 43 large CCS projects existing worldwide. The CCS technology still has not reached technical maturity, with high energy consumption requiring large-scale applications in the future. Consequently, CO_2 transport is required for its large-scale expansion, which is currently a weak link [60].

The costs for blue hydrogen are separated into two types. Blue hydrogen from natural gas has a price of around USD 0.99–USD 1.83/kgH_2 produced, while blue hydrogen from coal costs around USD 1.6–USD 2.05/kgH_2 [45]. The emissions associated with these production methods are 2.4 $kgCO_2/kgH_2$ for blue hydrogen from coal and around 1 $kgCO_2/kgH_2$ produced from natural gas.

3.2.7. Cost of Aqua Hydrogen

This type of hydrogen has been recently discovered in Canada and has no operating plant. The technique of using oil sands (natural bitumen) and conventional oil fields to extract hydrogen without carbon emissions is still very immature. Even so, the estimations about the costs associated with this method are merely low. It is expected that the extraction technique and treatment of this hydrogen have a cost of around USD 0.23/kgH_2 produced [45], being one of the cheapest methods, but with the condition that it can only be done in very specific spots.

3.2.8. Cost of White Hydrogen

White hydrogen corresponds to naturally occurring geological hydrogen that can be found in underground deposits and created through fracking. Some of these natural deposits can be seen in Figure 14 [61]. At this point, there are no clear strategies to exploit this type of hydrogen. The estimated cost of extracting white hydrogen is still about to be determined. Taking advantage of white hydrogen could be an important step to help low-carbon hydrogen production methods overcome traditional and polluting ones [61].

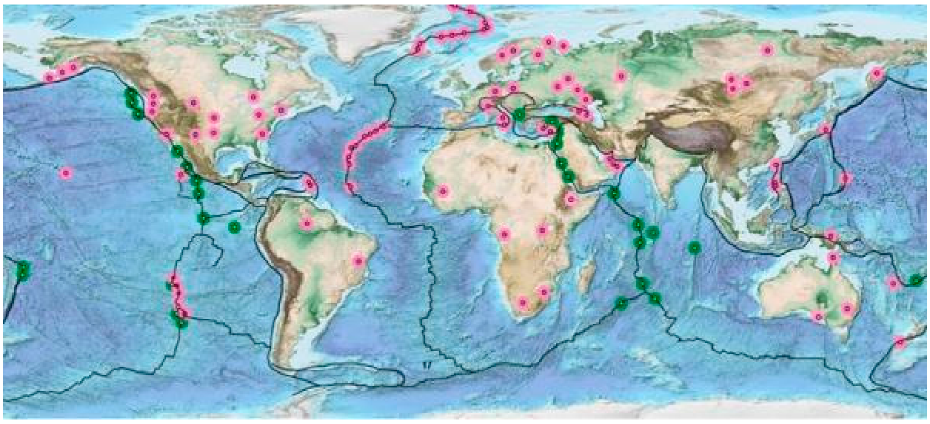

Figure 14. Spots where natural hydrogen can be found [61].

4. Conclusions and Future Prospects

Comparisons of costs and emissions can be made for the different hydrogen colors by identifying their specifications and collecting data from their economic assessment. It should be emphasized that all the prices appearing in this work are representative of the period 2021–2022. These prices will change slowly throughout the years, mainly decreasing for low-carbon technologies and becoming more competitive.

The main factor to be considered in this comparison is the range between cost and CO_2 emissions. The prices are expressed in USD/kgH_2, and the emissions appear in kg of CO_2 released into the atmosphere. Table 2 shows a summary of the results.

Table 2. Comparison between the hydrogen colors in terms of costs and carbon emissions.

Color	Cost [USD/kgH_2]	Emissions [kgCO_2/kgH_2]
green	2.28–7.39	0
purple, pink, and red	2.18–5.92	0
yellow	6.06–8.81	*
grey	0.67–1.31	8.5
black/brown	1.2–2.0	20
turquoise	2.0	**
blue	0.99–2.05	1–2
aqua	0.23	0

* Yellow hydrogen emissions depend on the location and its respective power mix. ** Turquoise hydrogen produces a solid carbon byproduct.

According to the data in Table 2, the cheapest hydrogen color would be aqua hydrogen. However, it should be highlighted that it has not been adequately tested and is still in an early stage. The following cheaper hydrogen colors are grey, black, and blue, which consume fossil fuels from natural gas to coal, and thus depend on their prices. Therefore, these are the most polluting ones, where black hydrogen is the less environmentally friendly, followed by grey hydrogen. Blue hydrogen still has some emissions, but the CCS system strongly reduces them.

Turquoise hydrogen has a considerably cheap cost, even though it is a technology that needs further testing. Its byproduct can be sold for several applications, and as it is solid, no GHG emissions are released. The other colors have the highest costs, starting with purple or pink hydrogen, where the energy comes from a nuclear plant. The production method is typically the electrolysis of water, which needs further improvement.

Green hydrogen follows with high production costs. These need to be significantly decreased to establish it as the leading production method. As mentioned, it is believed that its cost will not be low enough until the 2030s. Yellow hydrogen is the most expensive one, depending on the location and thus on the power mix used as the energy source. The composition of the power mix also determines the amount of generated emissions.

Thus, every different hydrogen production method has various factors to consider. Some of these methods have been mature technologies for years, such as SMR or gasification techniques. In contrast, others started to stand out in the last decades or have not even been explored much, as is the case with white hydrogen extraction, for example.

All of them are hydrogen sources that can be further explored to produce a larger amount of hydrogen and make it the primary energy carrier of the future. Unfortunately, all the technologies emitting significant GHG emissions need to be gradually abandoned. These technologies currently hold the highest maturity levels and lower costs. Therefore, low-carbon production methods must keep evolving and improving to achieve low costs without CO_2 emissions.

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