HYDROGEN ECONOMY – A BRIEF REVIEW

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Abstract. *Hydrogen has entered the energy strategies of many countries and economic unions all around the world due to the need of a new, universal and clean energy source, thus the formation of a hydrogen economy. Hydrogen can be utilized as an energy carrier, fuel for power and heat generation, fuel for vehicles, as well as feedstock in the production processes of other chemicals. In this article a very brief analysis of the hydrogen economy is performed, emphasizing on the methods for production and storage, the infrastructure for delivery and the possible uses of hydrogen. The costs and safety of production and handling are also discussed.*

Keywords: *hydrogen, economy, energy, carrier, fuel, power, electricity, storage, production, infrastructure*

1. Introduction

In the 21st century there are many environmental issues that become more disturbing from day to day – the increase of greenhouse gases (GHG) and of overall environmental pollution, the deforestation, and the vast depletion of fossil resources on global scale. Humanity is on the threshold of an ecological disaster and many communities and countries have already experienced at first hand the unnatural changes of our environment which imminently have led to many casualties and to serious economic and cultural damage. Due to this, the European Commission has launched the "European Green Deal" initiative with the aim to fully decarbonize our energy system by gradually increasing the share of clean energy from renewable energy sources (RES), and by prioritizing the overall efficiency of energy consuming industries by the mid-century. Realization of an interconnected and sustainable, digitalized energy market is also one of the main aims of the initiative (European Commission, 2019).

Hydrogen and electricity are envisioned to play the central role in such an energy system. The electricity of the future is going to be produced with zero GHG emissions by usage of RES such as wind, solar and tidal power, or by nuclear power. Due to the intermittent nature of RES and the inability of long-term electricity storage, the surplus electricity is going to be used for production of hydrogen via electrolysis of water, which is then going to be stored and used for electricity generation during periods of high energy demand (Mayyas et al., 2020). Apart from being an energy carrier, hydrogen is successfully utilized as fuel by employing fuel cell (FC) technologies for portable and stationary power generation, and transportation purposes with low to no emissions of harmful chemicals. Hydrogen is also vital for ammonia production which is a basic component of conventional fertilizers that help sustain the production of food globally for billions of people. Therefore, the consumption of hydrogen is forecasted to rise significantly in the next decades, see Figure 1, with the biggest consumers being the industry, power, transportation and synfuel production sectors (IEA, 2020).

In order to adequately reduce GHG emissions withing the set time terms, and to maintain economic growth, the European Union needs to apply well-coordinated policies throughout the whole value chain that also bring industrial, infrastructure, and market sectors together with the research and innovation perspectives in international scale (European Commission, 2020). Bulgaria, being a part of the union, should also well outline its plans for energy transition in the context of hydrogen economy in order to guarantee that its local companies and researchers stay competitive on the global technological and energy markets, and to maintain technological leadership and high job employment. Hence, the inspiration for this review which briefly highlights the main components of the hydrogen economy.

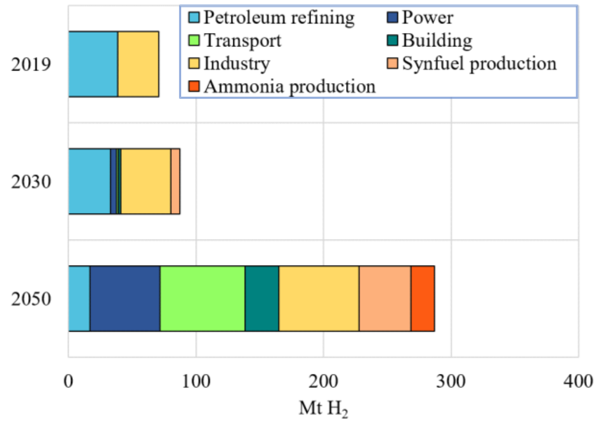

FIGURE 1. Global hydrogen demand by sector in the Sustainable Development Scenario, 2019-2050 (IEA, 2020).

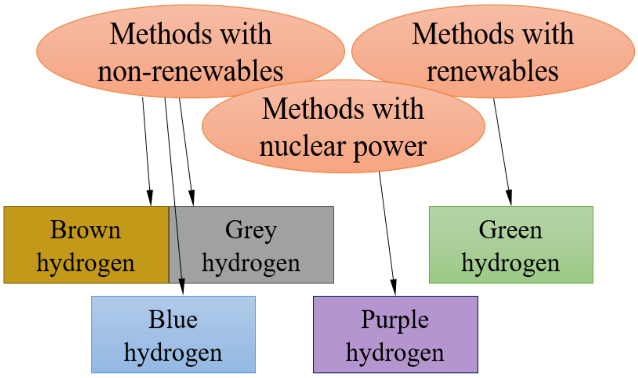

FIGURE 2. Hydrogen production method types and hydrogen color codes depending on the selected method.

2. Hydrogen production and storage

2.1. Hydrogen production

Hydrogen can be produced by a variety of methods making it a very versatile energy carrier. Different primary energy sources can be utilized in the production– thermal, biochemical, electrical, photonic, electro-thermal and others. The most widely-used division criterion in the production methods is whether the sources for production are renewable or non-renewable. On the other hand, hydrogen can also be divided in categories depending on the production method, such as: green hydrogen – produced by electrolysis powered by RES, purple hydrogen – produced by electrolysis powered by nuclear energy, blue hydrogen – produced from natural gas with carbon capture, utilization and storage (CCUS), grey hydrogen – produced from fossil fuels (most commonly natural gas) without CCUS, and brown hydrogen – produced as a by-product in industrial processes or from coal without CCUS– see Figure 2. CCUS is the process of capturing CO_2 before it enters the atmosphere, transporting it and storing it in geological formations such as salt caverns or coal beds, intending to mitigate the effects of climate change (Chen and Chen, 2020).

The production of hydrogen from non-renewable sources, that are the fossil fuels, is a complex, yet mature process, which guarantees relatively high efficiencies (60-

85%). In 2019 roughly 75 million tons of hydrogen were consumed, 96% of which was grey hydrogen from fossil resources (da Silva Veras et al., 2017). Steam methane reforming is the most common method of this type – natural gas, that mostly consists of methane, and steam, react together over a catalyst at high temperatures. Desulfurization in advance is required in order not to poison the catalyst. Water gas shifting (WGS) is also employed in the end of the reforming process to obtain further amounts of H_2. Other methods from the same type include standard partial and partial catalytic oxidation of natural gas, auto-thermal reforming of natural gas, and coal gasification – see Figure 3. The mentioned methods are well known and commercial and all of them, expect for the gasification, guarantee high conversion efficiency and high purity of the product. However, they all utilize fossil fuels, and since CCUS is in early stages of development, such hydrogen production bears the problem of negative environmental impact. Moreover, even if CCUS is effectively applied, fossil fuels are depletable, therefore the strategy to achieve a decarbonized energy system aims at slowly decreasing the dependence on fossil fuels for hydrogen production until 2050, which is also a good time reserve for RES technology and infrastructure to get developed and constructed.

Water electrolysis with electricity generated from RES is the most common method for production of green hydrogen. It requires an electrolyzer – a device that consists of electrodes, a catalyst and an electrolyte – which splits water to hydrogen and oxygen at very high efficiencies of up to approximately 85%. Three proven electrolyte technologies are used for this process – alkaline, proton exchange membrane (PEM) and solid oxide (SO), PEM being the most cost-efficient, researched and commercially available one. Electrolyzers can produce hydrogen with high purity (up to 99.99%), they are compact and have stable operation at various ambient conditions. Photolysis is another way to split water but a photoelectrochemical cell is used – a device that combines photovoltaic panels and an electrolyzer. Such devices, though, are not efficient enough and have very strict material requirements (John Turner et al., 2008). Thermolysis of water is also an option for harvesting of hydrogen, but it requires very high temperatures and/or catalysts while its efficiency is around 30% lower than the one of electrolysis, the process is expensive and its heat management is complicated. It can be conducted by using renewable energy, by burning fossil fuels, or by using nuclear power.

There are also various biological processes for H_2 production – biophotolysis for example is achievable by using certain algae that release hydrogen gas when illuminated by sunlight in the absence of oxygen. Alternatively, other types of algae photosynthesize hydrogen instead of oxygen when deprived of sulfur. Fermentation processes of various organic compounds can also generate hydrogen in specific types of bacteria. The methods for production of biohydrogen are innovative and environmentally friendly, but they are still in the demonstration phase of development and have unsatisfactory efficiency levels which indispensably lead to usage of very large bioreactors or algae farms. Therefore, at present, electrolysis is more prospective than the biological methods for hydrogen production. A different variant is gasification of biomass, which in comparison to coal is a renewable source available from a number of animal and plant waste products, crops and forest by-products (Lepage et al., 2021). This method, however, has significantly lower efficiency than electrolysis and also requires very big quantities of continuously supplied feedstock to the gasifier.

Based on the facts stated above, the priority of the European Union is to namely develop hydrogen production facilities mainly adopting solar and wind power. In the first phase of the strategy up to 2024 at least 6 GW of renewable hydrogen electrolyzers are to be installed and up to 1 million tons of renewable hydrogen produced (European Comission, 2020). Of importance remains the question of hydrogen storage, which is discussed in the next subsection of the publication.

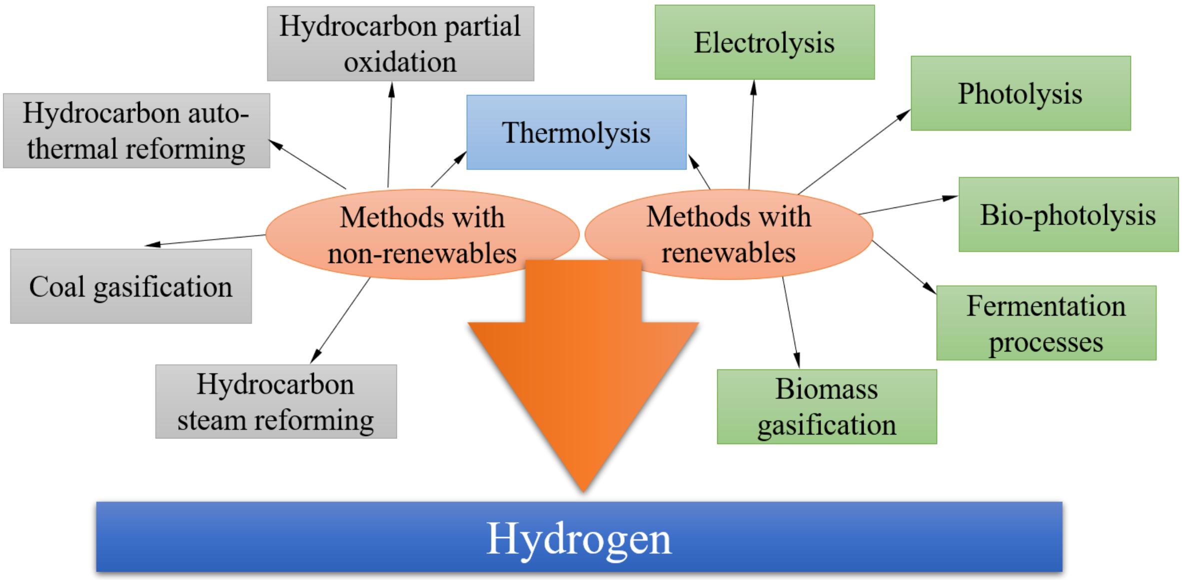

FIGURE 3. Hydrogen main production methods.

2.2. Hydrogen storage

Storing hydrogen is a demanding task as it has very low density by volume. The type of storage depends on the application, needed quantity, safety requirements and the planned delivery distance. The most common method for long-term and large-scale storage is as a pressurized gas, most typically at 20, 35 or 70 MPa. There are many different types of pressure vessels, generally divided in 5 types, Type I being fully metallic, while Type V – built entirely from composite materials, the types in-between have a hybrid metal-composite structure (Moradi and Groth, 2019). The technology is mature, simple and commercially available, it is also employed in fuel cell hybrid electric vehicles (FCHEV) such as the Toyota Mirai. Naturally, there are some disadvantages of the technology – the hydrogen volumetric capacity is still relatively low even at 70 MPa pressure, the vessels made out of composites are very sensitive to high temperatures and fire, and generally all types of storage reservoirs are heavy.

Liquid hydrogen storage assures better volumetric capacity – around three times the one of pressurized storage at 35 MPa, yet it is a very challenging method. Liquification requires cryogenic temperatures of -253 °C, consumes much more energy than pressurizing and the daily evaporation of hydrogen from the vessel should be managed, because the boil-off process occurs constantly due to the heat exchange with the ambient environment. This method is believed to be more reliable for large-scale storage and delivery over long distances in installations that are adjusted for capture of the evaporated H_2 (Zhang et al., 2016). A compromise option is the cryo-compressed type of storage which combines the advantages of both the abovementioned methods – good volumetric density at lower pressures than 35 MPa, but cryogenic temperatures, with possible fueling with both liquid and/or gas hydrogen. Currently, this method is still in the demonstration phase of development.

An option for hydrogen storage that attracts a lot of interest is chemical bonding in the form of metal hydrides (MHs). Many different metal hydrides exist that offer independently from one another either good volumetric and gravimetric capacities, or simple and cheap production and maintenance, or long-term stable operation. Low sensitivity to change of ambient conditions, low temperature and energy for the hydrogenation and dehydrogenation processes, and low sensitivity to hydrogen purity are also required. Until now there has not been a metal hydride that fulfils all the requirements mentioned above, which hinders the widespread application of this technology. Nonetheless, the continuous research oriented toward betterment of the MH characteristics promises good results in the years to come (Durbin and Malardier-Jugroot, 2013).

Chemical storage of H_2 is also achievable by surface adsorption in solid metals – it guarantees fast kinetics and low energy demand for the bonding, yet it is not so prospective due to the low capacity and the need of thermal management. Researchers have been studying storage of hydrogen as ammonia, hydrocarbons or liquid organic hydrogen carriers (LOHC) – see Figure 4. All these chemicals can make use of the already built infrastructure for transport. However, they either have low hydrogen release kinetics, or low storage capacity, or the released hydrogen needs additional purification before use.

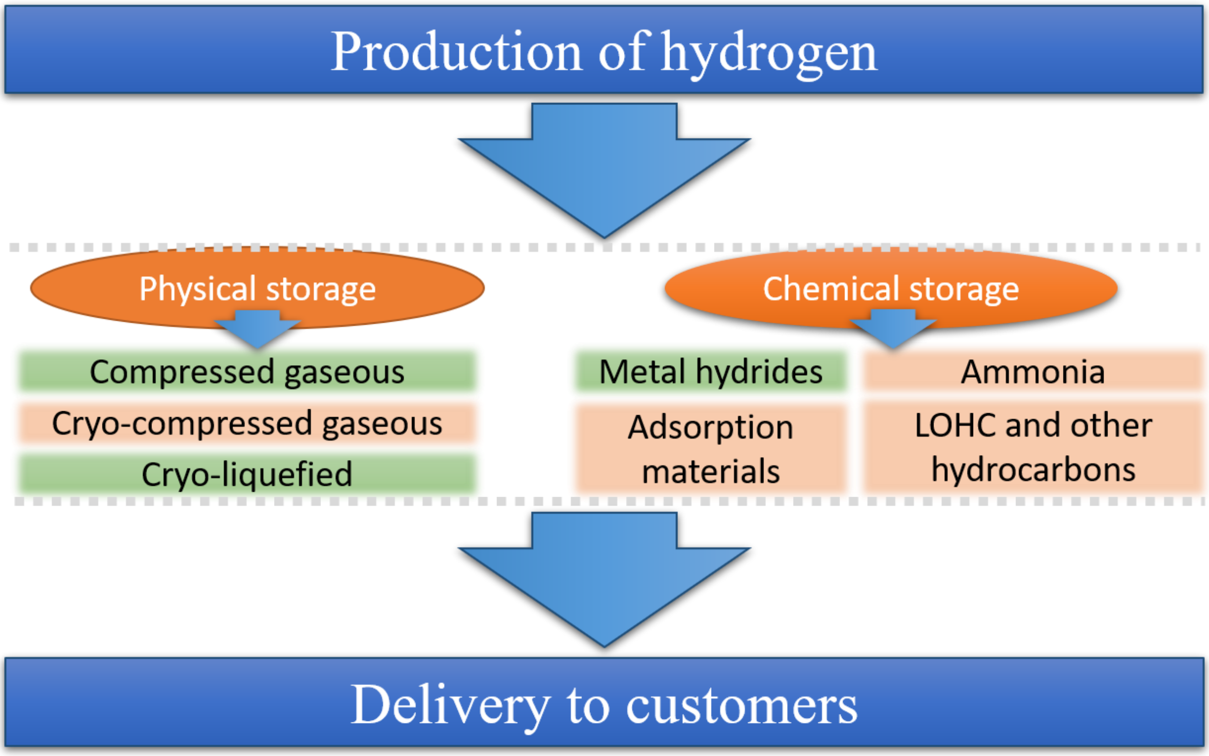

FIGURE 4. Hydrogen main storage methods. Green-colored methods (compressed gaseous, cryo-liquified, MH) are commercial.

Presently, the most frequently used methods on large scale are of pressurized gas hydrogen or liquified hydrogen. The aim is to further develop the other technologies and eventually integrate all of them into a robust storage system with different storage options depending on the needed quantity and application of hydrogen. Such a system is admittedly invalid in the absence of an adequate infrastructure for fast delivery of the fuel to customers.

3. Hydrogen delivery and infrastructure

Transport of hydrogen is mainly dependent on the storage method. Gaseous hydrogen for example, can be transported in pressure vessels loaded on ships, heavy-duty trucks or train wagons, or transported via traditional pipeline systems. Pipelines are potentially the most cost-efficient and easy method for delivery of big quantities in the long-term. There are certain drawbacks, tough, such as the degradation of the metal coatings that come in contact with the hydrogen, which can be dealt with by introducing a mixed natural gas-hydrogen gas delivery where the H_2 is no more than 17% by volume (Gondal and Sahir, 2012). The other methods of gaseous hydrogen transportation are viable for shorter distances. Trucks loaded with tube trailers for example, are going to be employed for deliveries to the end consumer fueling stations in the same way gasoline and diesel fuels are delivered. Additionally, truck hydrogen transportation is the most accessible for the short- and mid-term strategies of the hydrogen economy development. Usage of tube trailers is also suitable for delivery of hydrogen to more remote, or inaccessible locations, where it is harder to install a pipeline or there are no ports for deliveries by ship. Nonetheless, pressurized H_2 delivery with trucks is not very cost-efficient, because the payload is only up to 10% of the vehicle's total mass due to the low gravimetric capacity of the cargo. Ship and wagon hydrogen transportation are more appropriate for longer distances and larger quantities, thus liquid hydrogen, is most commonly thereby transported. Ammonia, LOHC and hydrocarbons that are intended for hydrogen production are delivered to the dehydrogenation sites via well-known methods for liquid and gaseous fuel transportation, but such storage methods, as discussed above, are still not applied massively. The H_2 delivery methods are listed in Figure 5.

Regarding infrastructure, probably one of the biggest challenges is to build a well-organized and widespread pipeline network that can transport higher capacities of hydrogen at high pressures. Building a robust fueling stations network is also a serious challenge. A very good approach that is expected to be utilized massively due to its simplicity and lower cost is directly installing production and storage facilities (solar panels, electrolyzer and pressurized gas reservoirs) at retail fueling stations or near them, locally, where a few stations could be supplied simultaneously. This way the need for inefficient tube-trailer deliveries would be reduced.

Hydrogen forms an explosive mixture with oxygen in a very wide range of proportions and leakages are very dangerous in enclosed spaces such as underground parking lots. The oxygen-hydrogen flames are merely invisible to the naked eye due to their ultraviolet color and hydrogen is odorless, therefore it is hard to detect a leak. Naturally, there exist certain safety requirements that follow set engineering standards when handling hydrogen and fuels in general. For example, at fueling stations supplied by trucks – tube trailers should undergo penetration and leak tests, pressure and temperature cycle tests and others, the same applies for storage vessels at the station; the hydrogen has different maximum pressure and temperature values for each of the cases when transporting, storing or charging; and others (Moradi and Groth, 2019). Many of these standards are about to get further specified in the coming years as hydrogen utilization becomes more common. It is also important to well teach and advocate about the qualities of hydrogen in order to lower the public concern.

4. Hydrogen uses, perspectives and cost

There are numerous applications of hydrogen, as nowadays the use is mainly dominated by the industry: production of ammonia and methanol, steel production, oil refining, and even production of pharmaceuticals and food, and in that case, it is produced directly in or in the vicinity of the industrial plant where it is used. Nonetheless, hydrogen has many potential applications in other sectors as shown in Figure 1. In power generation, hydrogen is one of main options for renewable energy storage, it can also be utilized in gas turbines to increase flexibility of the system, or directly burnt in conventional power plants to reduce harmful emissions. Likewise, in the transport sector, hydrogen is used in conventional internal combustion engines (ICEs), being mixed with gasoline or diesel in a gas-fuel mixture, again to reduce emissions. For residential purposes it could be blended in the existing natural gas network to heat homes and commercial buildings in big cities – see Figure 5. There is also a concept for a hydrogen village which is entirely powered by renewable hydrogen (Jain, 2009).

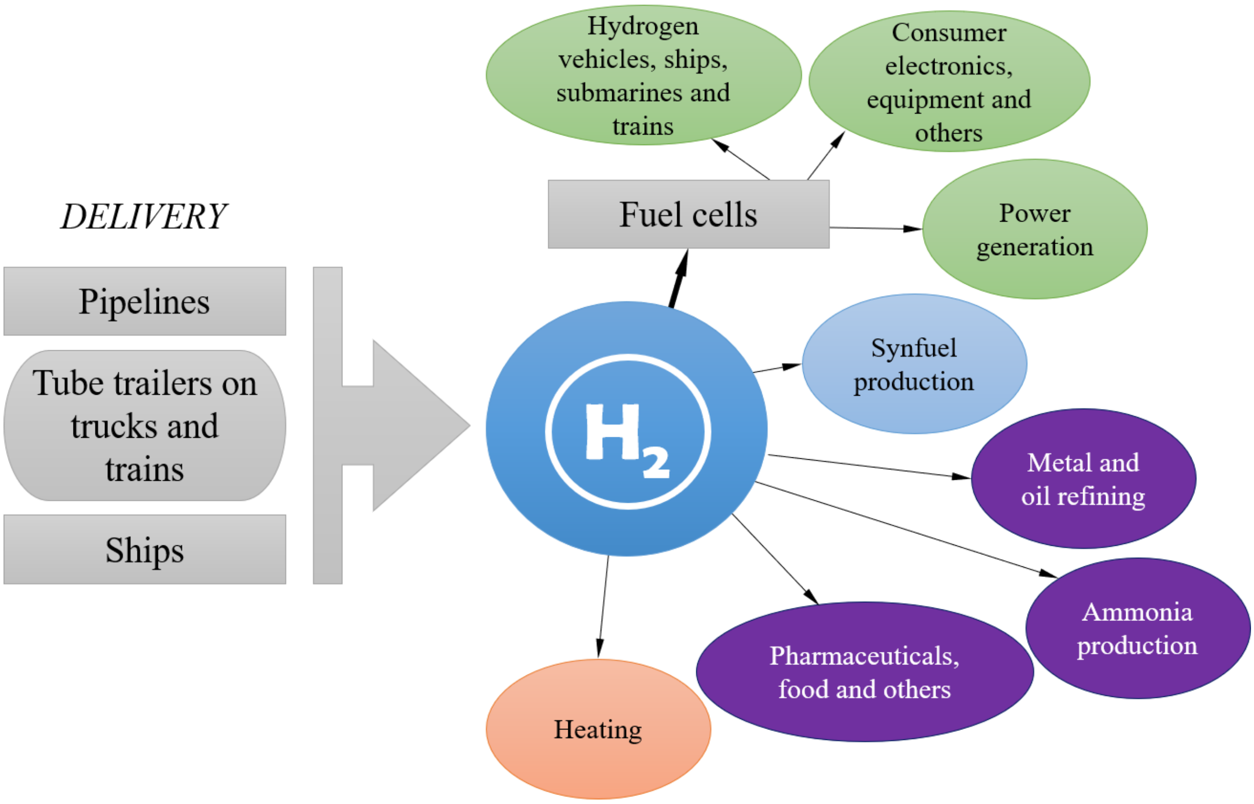

FIGURE 5. Hydrogen delivery methods and uses.

The most promising and prospective use of hydrogen is as fuel in fuel cells. Fuel cells are electrochemical devices that transform the chemical energy of the fuel into electricity and they consist of the same elements as an electrolyzer. FCs are superior to ICEs due to lack of combustion and thus their higher efficiency which can be up to 60-65%. FCs are also superior to batteries as they have a longer lifetime and work as long as the feedstock (fuel and oxidant) are continuously supplied to them.

There exist many various types of FCs based on the type of electrolyte; geometry; the used fuel – hydrogen, ammonia or other hydrocarbon; the operating temperature and pressure; the power ranges; and others. There are a few popular FC types that have been extensively researched and have already achieved some degree of commercial success: Proton Exchange Membrane FC (PEMFC), Alkaline FC (AFC), Phosphoric Acid FC (PAFC), Molten Carbonate FC (MCFC), Solid Oxide FC (SOFC) and Direct Methanol FC (DMFC).

The compact design of FCs and their advantages over other power generation systems guarantee them a number of application possibilities – portable and backup power applications, transportation and stationary power applications. In the portable sector they are suitable for power generators for light personal (such as camping) and light commercial uses (for surveillance for example). Other portable FC applications are electronic devices – notebooks, smartphones, radios, battery chargers, military equipment, RC electronics, etc. Such FCs are a compact, long-lasting, lightweight power source without need of recharging, even though fuel storage still remains an issue. The most common types for such utilization are PEMFCs and DMFCs (Spiegel et al., 2007).

Backup power systems provide power when the main power source fails and they come in a wide range of sizes and types. Some of the possible applications include homes, computer systems, telecommunication systems and manufacturing systems. In this case the critical parameter is not efficiency, but response time. PEMFCs are mostly implemented in such cases.

Transport applications of FC represent serious interest to researchers in their search for ICE replacement. FCs could be employed in cars, buses, heavy-duty and utility vehicles, trains, submarines, ships and others, with many prototypes and even few commercial projects already realized (Spiegel et al., 2007). Mostly PEMFCs are used for such purposes but also PAFCs, DMFCs, MCFCs and SOFCs give promising results. In transport means fuel cells can play the role of main power unit (MPU) or an auxiliary power unit (APU).

In principle all types of FCs can be utilized for stationary power for small to middle-sized power plants in remote areas or for back-up supply, as well as large-scale power plants for distributed power and also cogeneration. They have great commercial potential and architectures vary depending on size, stack type, heating and cooling aggregates of the stack, and fuel type. Power output is the range between a few kilowatts to few hundred megawatts. Such systems have high efficiency and commonly utilize natural gas or other conventional fuels. The start-up times are not so important and all the output products could be consumed by the local community to higher the overall efficiency.

There are also many perspectives in the development of production and storage methods for hydrogen. The aim is the make production more efficient, while storage would be safer and requiring less maintenance. In terms of FC development, researchers are seeking for alternative materials that would guarantee more efficient and more stable operation at lower cost. Especially for catalysts, it is important to utilize cheap chemical elements that have lower propensity to getting poisoned by impure fuel, oxygen or carbon dioxide. Innovative production technologies are also believed to better the cost-efficiency and the quality of the end products.

New types of FCs that employ a different electrolyte are also being developed. Moreover, new hybrid power systems, containing a FC in their architectures, are becoming popular. Combined SOFC/gas turbine and SOFC/ICE hybrid cycles for example, are modelled and built for stationary cogeneration to supply factories or even small communities (Buonomano et al., 2015). Such advanced technologies ensure very high efficiencies (higher than standalone-SOFC systems) with low environmental impact.

Certainly, cost is determining in applying new energy technologies and approaches and it is one of the main hurdles for the hydrogen economy as well. According to the report of the European Commission (European Comission, 2020), as of 2020, the cost of producing green hydrogen in Europe is in the range 2.5-5.5 €/kg, which is comparable to the green hydrogen prices worldwide. In comparison, grey hydrogen costs just 1.5 €/kg and blue hydrogen is estimated at around 2 €/kg. Moreover, at present the FC hybrid electric vehicles such as the Toyota Mirai cost significantly more (start around 50.000 $) (Toyota Official Website, 2021), than a comparable class car utilizing an ICE. Countries where such automobiles are available (mostly Japan, US and some European countries) offer incentives for buying such a zero-emission vehicle, such as tax benefits, lower price and/or free fuel for a few years or for a set millage. Nonetheless, their price is still very high, and in combination with the lack of a robust fueling stations network, it is a push for most customers to prefer traditional ICE-driven vehicles. Namely the lowering of the green hydrogen price down to 1-1.5 €/kg, and the price of FC hybrid electric vehicles to parity with the gasoline and diesel vehicles, is a part of the strategy of the European Union in the next ten years.

5. Conclusions

The hydrogen economy concept where hydrogen is envisioned as a universal energy source alongside electricity is slowly gaining strength as numerous new commercial and scientific projects for hydrogen production, storage, delivery and utilization are launched every year by the leading global economies and economic unions. The main aim of the projects is to make the hydrogen technology more well-known among the society and to establish efficient, cost-effective, safe and sustainable practices for its handling. H_2 is believed to be an environmentally friendly replacement of fossil fuels and is planned to be produced mostly by renewable energy sources to be utilized in many sectors such as transportation, industry, agriculture and others. Fuel cells are massively used with hydrogen fuel as they provide high efficiency, compactness, stable operation and possibility for embedment in various applications. The biggest roadblock for hydrogen is its cost, but with the further development of storage and delivery methodologies, and with the building of widespread production, delivery and fueling networks, the cost is expected to lower, becoming more competitive to the one of conventional energy carriers.

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