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Clean Energy Catalyst: The Rise of Green Hydrogen

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Abstract

Green hydrogen is produced from water and solar, wind, and/or hydro energy via electrolysis and is considered to be a key component for reaching net zero by 2050. While green hydrogen currently represents only a few percent of all produced hydrogen, mainly from fossil fuels, significant investments into scaling up green hydrogen production, reaching some hundreds of billions of dollars, will drastically change this within the next 10 years with the price of green hydrogen being expected to fall from today's US$ 5 per kg to US$ 1–2 per kg. The Australian Government announced a two billion Australian dollar fund for the production of green hydrogen, explicitly excluding projects to produce hydrogen from fossil fuels, like methane. This article reviews current perspectives regarding the production of green hydrogen and its carbon footprint, potential major applications of green hydrogen, and policy considerations in regards to guarantee of origin schemes for green hydrogen and hydrogen safety standards.

Keywords: green hydrogen, production, applications, guarantee of origin, safety standards

1. Introduction

Hydrogen is the most abundant element in the universe. Using it for the production of electric and thermal energy appears to be a reasonable option. However, on Earth, hydrogen rarely occurs as pure hydrogen, but it is bonded to predominately oxygen forming water. The bond between the oxygen atom and the two hydrogen atoms in water is very strong and, therefore, significant energy is needed to split hydrogen from oxygen.

To split water, either electrolysis and/or chemical reactions are used. Electrolysis uses electric power to split water into hydrogen and oxygen. The chemical reaction process generally uses coal and steam. While hydrogen is set, free oxygen forms a new bond with carbon, forming CO and CO2. The other chemical reaction process oxidizes natural gas, releasing hydrogen and forming CO2. Methane is the predominant source of hydrogen production, accounting for about 65% of the total hydrogen production of about 70 million tons per year, followed by coal. Currently, electrolysis accounts for only for a very small fraction of H2 production.

The use of green hydrogen to decarbonize power production, mobility, and a number of industrial processes, like steel, cement, lime, alumina, and fertilizer production has been at the forefront of developments to reduce CO2 emissions, address climate change and reach net zero emissions by 2050. Currently investments of hundreds of billions of dollars are announced for hydrogen projects worldwide [1].

This article reviews technical and socio-economic key considerations for the development of a green hydrogen industry which provides the reader a holistic insight into the many facets of the emerging green hydrogen industry.

1.1. The colors of hydrogen

The current way to label hydrogen from the various production processes is applying a colour code (Table 1). Green hydrogen is produced from water using electrolysis run solely by wind and solar energy or hydropower. Blue hydrogen is based on methane and uses carbon capture and storage to reduce CO2 emissions. Grey hydrogen also uses methane, but without carbon capture and storage. Turquoise hydrogen uses methane, but the process forms solid graphite as a by-product, not CO2. Pink hydrogen uses nuclear power to split water. Black hydrogen uses black coal, while brown hydrogen applies brown coal. Finally, there is natural gold hydrogen formed through geological processes within the Earth's crust which are not linked to oil and natural gas formation, but a reaction of water with iron oxide in the rocks at high temperatures and pressures.

Table 1. Color coding of hydrogen.

Type of hydrogen	Type of hydrogen Production
Green hydrogen	Electrolysis of water using only renewable energy sources
Blue hydrogen	Methane reforming with carbon capture and storage
Turquoise hydrogen	Methane pyrolysis forming hydrogen and solid carbon
Grey hydrogen	Methane reforming
Black hydrogen	Reaction of water with black coal
Brown hydrogen	Reaction of water with brown coal
Pink hydrogen	Electrolysis of water using nuclear energy sources
Yellow hydrogen	Electrolysis of water using fossil fuel-based energy sources
Gold or white hydrogen	Naturally occurring hydrogen in geological formations

Of all these types of hydrogen, green hydrogen production appears the only truly sustainable process which is free from greenhouse gas emissions and other by-products, apart from oxygen. Gold hydrogen is also free of any by products, but because it is mined, it does not fall under the 'sustainable' banner. However, as a gap filler until the production of green hydrogen is at scale, gold hydrogen may play a future role. Recent discoveries of potentially huge gold hydrogen resources in Western Australia and South Australia are providing a potentially promising source of carbon free hydrogen [2]. To produce the current world-wide hydrogen output via electrolysis about the total annual electric power generation of the European Union from all sources is needed. However, in order to have green hydrogen, this amount of electric power needs to be solely produced from renewable energy sources.

2. Production of green hydrogen

By definition, green hydrogen must be produced from water via electrolysis using only renewable energy sources, i.e., solar, wind, and hydro power. Green hydrogen can be produced wherever water and green energy is available which provides a very flexible and scalable scenario.

2.1. Technologies for production

Sustainable and clean hydrogen production techniques are recognized by two characteristics, i.e. the type of energy inputs and the feedstock, each of which must be obtained by clean means. Renewable energy in its various forms, such as electricity as in electrolysis or heat as in thermochemical processes, are deployed and used to extract hydrogen from renewable feedstock, as water or biomass [3].

The potential of using water for producing clean hydrogen is categorized by high-temperature dissociation, thermochemical processing, electrolysis and photolysis using external energy in combination with renewables. The electrolysis process combined with a variety of renewable energy sources is the most promising green hydrogen generation method. When two electrodes are submerged in water and an electric current is passed through water, the medium is split between hydrogen and oxygen giving the way for electrolytic generation [4]. Figure 1 shows a variety of electrolysis configurations depending upon the electrolyte used.

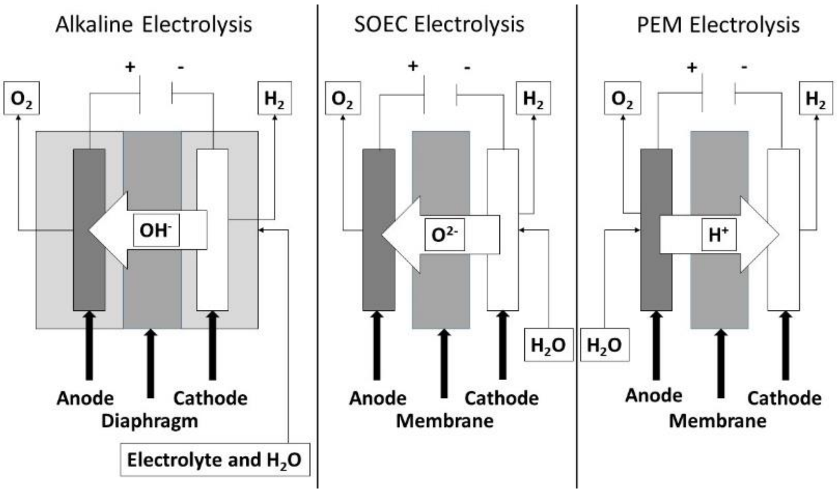

Figure 1. Three types of water electrolysis.

Traditionally, alkaline electrolysis is widely applied at the commercial scale where NaOH or KOH are used as electrolytes for their technological and infrastructural conveniences. A disadvantage of this process lies in the fact that it has low efficiency (50–65%) with a moderate current density of 0.1–0.4 A/cm2 [5] and uses an extremely corrosive electrolyte [6].

Meanwhile, exchange membranes coupled with hydrogen technologies can store and distribute large amounts of energy, which is particularly significant for the transportation sector. In this process, a polymer exchange membrane (PEM), e.g., NAFION, acts as an electrolyte medium facilitating the flow of protons (H+) in the following reaction. In comparison to alkaline electrolysis, the process observes a higher current density (>1.6 Amp/cm2) with higher overall efficiency of 50–75% [5].

By using a solid medium, like zirconium dioxide, for solid oxide electrolysis cells (SOEC) based electrolysis process, the Ohmic resistance is significantly reduced which increases greater facilitation of molecular kinetics and thermal conductivity [7]. Moreover, the SOEC electrolysis process happens endothermic at high temperatures. The desired energy can be easily fed through existing thermal or nuclear reactor plants' available waste heat [8]. SOEC is not commercially viable yet. Nonetheless, recent developments in integrated solid oxide fuel cum electrolyse cells (SOFC/SOEC) in combination with solar-powered operated organic Rankine cycle offers substantial optimism [9].

Currently, electrolyser producers are ramping up production, as they realize the rise of hydrogen in future. Alkaline, PEM and SOEC are among the common technologies for electrolysers in producing green hydrogen, but with different maturity and hydrogen purity level, as shown in Table 2. While PEM electrolysers have a higher efficiency of more than 80%, they are more expensive due to the use of noble metals for the process and the membrane is subject to degradation over time. On the other hand, alkaline electrolysers are a well-established technology in use for many decades, but have their efficiency falling in the 70% range.

Table 2. Electrolysis process features and their present maturity level.

Type	Features	Maturity
Alkaline	High energy consumption with low-pressure H2 yield. Low purity process [10].	Highest maturity level amongst all three electrolysis processes. A plant with a production capacity of 1200 kg/hr is running
PEM	It can operate at high pressure and is more compatible with renewable coupling [11].	Low maturity level in the current stage but expected to achieve gigawatts productions level in future. High lifetime cost with frequent maintenance need poses commercial barriers [12].
SOEC	Capable to operate at high temperatures. Good choice for waste heat recovery option [13].	In the lab development stage. Long term stability and material-related challenges are major commercial barriers [14].
Power to X (PtX)	The futuristic electrolysis process can be coupled with a range of industries including transportation, HVAC, chemical etc with the help of renewable integration [15].	Research stage only. In long term, successful industry-wide renewable integration could transform range sectors [16].

It is well established that electrolysis process efficiency can be significantly increased using high temperature mainly due to two factors. First, part of the energy requirement for chemical reactions is fulfilled by heat itself. Second, the electrolysis process itself expedites the due to higher ionic motion at higher temperatures [17]. Moreover, a technical analysis performed by Baeda et al. [18] concluded that the efficiency can be further improved if it is used in conjunction with concentrated solar radiation making it a commercially viable option for the industry.

From a thermodynamics standpoint, the minimum electric energy requirement demand in any electrolysis process is given by Gibbs free energy (ΔG), which can be defined in the below equation:

$$\Delta G = \Delta H - T\,\Delta S \tag{1}$$

Where,
Δ H: enthalpy change,
Δ S: entropy change,
T: temperature

As shown in the Eq 1, the required electrical energy can be compensated with the addition of heat and a temperature rise [19]. The technological review suggests the ratio of electricity ΔG and heat ΔH is around 93% at 100 ℃ which can be brought down to 73% with additional heat of 1000 ℃ in the process [19]. Therefore, SOEC combined with waste heat from e.g., green steel production and renewable energy appears to be an efficient alternative for green hydrogen production. However, such concepts are not yet realized and would require further detailed studies and sophisticated system engineering approaches.

For a small hydrogen plants, the selection of the most effective processes with the highest efficiencies is of utmost importance. High temperatures hydrogen generation technologies offer optimism for two reasons. First, part of the energy requirement is fulfilled as heat that improves system efficiency. Second, the reaction rate of electrolysis itself becomes faster due to higher ion mobility [20,21].

For example, literature studies of a technical nature highlight that when the solid oxide electrolysis (SOE) method is used in conjunction with concentrated solar energy (CSE) for attaining high temperature, the efficiency of the whole system further improves because the foundation of both technologies are same. Li et al. suggest that higher system temperatures (700–900 °C) of the process significantly reduce dependence on the noble catalyst with superior efficiency levels of 80% [22,23].

2.2. Role of water quality in electrolysis

It is of utmost importance that water used in electrolysis process must be free from impurities, desalinated and demineralized because the electrolysers are highly sensitive to it. For instance, during the PEM electrolysis process, feeding saline water may yield ionic chlorine instead of oxygen at the cathode. Some studies suggest the usage of certain catalysts, e.g., magnesium, to maintain water purity while impending chlorine formation is an undesired outcome of the electrolysis process [24].

To produce hydrogen from salty water, e.g., seawater, from commercial electrolysers using the PEM electrolysis process, the American Society of Materials (ASTM) section-II recommends an extremely restrictive maximum allowable sodium and chloride content of 5 mg per litre and less than 50 ppb of total organic carbon (TOC). Although alkaline electrolysers are relatively more flexible than their PEM counterparts most of them use a variety of ways to maintain water purity such as reverse osmosis (RO), multiple effect distillation (MED), or electrodialysis (ED) [25,26].

When dealing with desired water purity, extant studies often delve into efficient seawater electrolysis processes, available technologies, and a combination of them. A schematic diagram for the hybrid electrolysis combined with reverse osmosis process is indicated below (Figure 2).

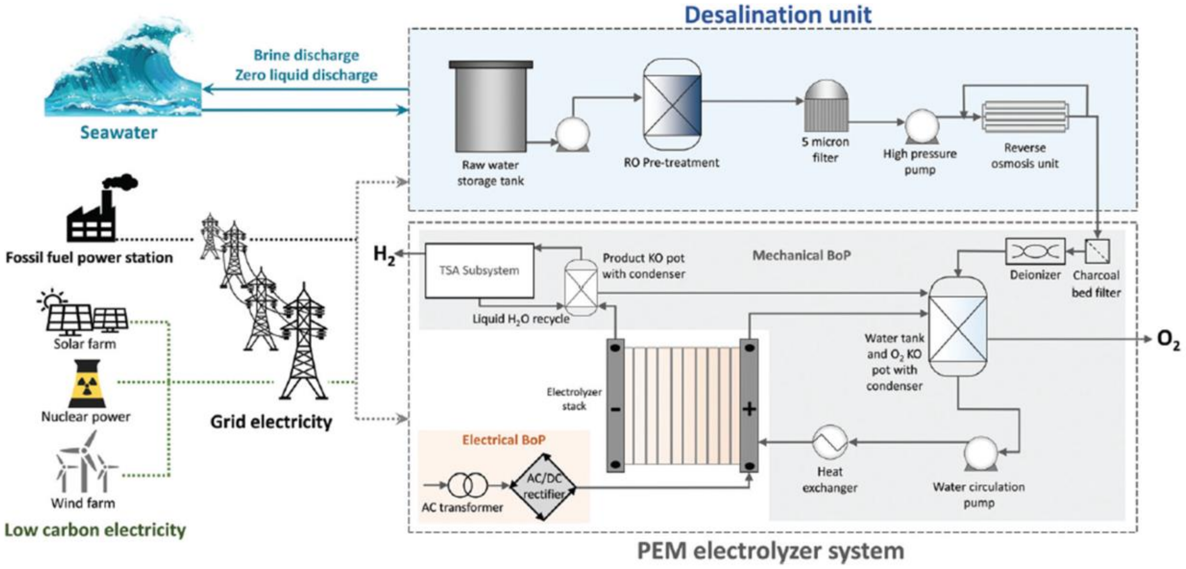

Figure 2. Coupling of (PEM) electrolysis with RO can meet desired water quality for hydrogen generation [26].

Given the rise in affordable desalination technologies suitable for hydrogen electrolysis, total production capacity has clinched the 100 million m3 mark per day with a price of about $ 0.6 per m3 primarily generated by reverse osmosis having a 70% share [27]. New discoveries, like direct seawater splitting to produce hydrogen are promising developments which indicate that this sector will see significant improvements in efficiency and cost reduction of desalinated water [28].

In summary, from the hydrogen economy’s standpoint, green hydrogen is expected to witness heavy demand not only as a source for clean fuel and energy carrier, but also as a key input for numerous industrial sectors steel making, chemical, ammonia and fertilizers and many others [5].

Many countries, including Australia, have already set the growth targets to dramatically boost green hydrogen production. Australia, together with the United States and Spain, is expected to be among the top-tier countries that will have the annual green hydrogen production capacity to reach or surpass 2 million tons per year by 2030. Other countries, especially in North Africa, South America and the Middle East are also expected to develop substantial green hydrogen production capacity.

In order to provide sufficient green energy for the production of green hydrogen in Australia, the entire current green energy generation in Australia, which is about 32.5% of the total energy production, needs to be doubled. While this appears very demanding, it sounds less problematic when considering that Australia already doubled the renewable energy output between 2017 and 2022. According to the Clean Energy Council [29], by early 2022, 131 renewable energy projects were under construction or have reach financial close totaling $ 25.5 billion in capital investments and providing more than 17 GW in renewable energy output. Most recently, the Asian Renewable Energy Hub in the Pilbara started and will generate up to 26 GW of wind and solar capacity to produce 1.6 million tons of green hydrogen per year at a total estimated investment of about $ 36 billion [30]. In addition, Fortes cue Future Industries has struck a potential $ 50 billion green hydrogen agreement with German energy giant E. ON to produce and ship from Australia to Germany up to five million tons of green hydrogen per year from 2030 on. This project will also lead to production of 60 to 70 GW of renewable energy [31].

Recently, developed direct seawater electrolysis has opened a new avenue to produce low-cost green hydrogen, because it reduces the need for water purification. The main challenge of direct seawater electrolysis is the degradation of the anode and cathode of the electrolyser by the dissolved salts in seawater and the formation of reactive oxygen through during the seawater electrolysis. Several concepts for direct seawater electrolysis have been developed applying changing the pH of the seawater before electrolysis or specially designed catalysts. While these methods provide a very promising approach to use seawater for lower cost hydrogen production without any pre-treatment of the seawater, it still has to be commercialised, tested in up-scaled pilot plants, and properly costed for large scale green hydrogen production [32,33].

Another method to specifically address the effect of reactive oxygen formed during seawater electrolysis is the so-called hybrid seawater electrolysis. Here, the reactive oxygen is simultaneously used for biomass oxidation or production of chemicals like urea to avoid damage of the electrolyser components by the reactive oxygen. In addition, the use of the oxygen from electrolysis for the production of chemicals may have a beneficial value adding effect. Again, commercialization, efficiency in large scale application, and costs of this process still have to be established [34].

2.3. Price of green hydrogen

Many countries decided to engage in decarburization strategies and hydrogen will be essential to achieve this, especially in sectors where direct electrification is difficult to realize, such as steel, chemicals, long-haul transport, shipping and aviation. In addition to the necessity to have hydrogen with a very low carbon footprint, the cost of producing green hydrogen is a major hurdle. Currently, with a price of about US$ 5/kg of green hydrogen is still 2 times more expensive than blue hydrogen and three times more expensive than grey hydrogen [35]. Therefore, cost reductions are essential not just to compete with blue or grey hydrogen, but to provide a cheap and reliable energy source for decarbonizing the society. However, strategies are in place to bring the price of green hydrogen down to US$ 1/kg [36]. The cost of the renewable electricity is the major cost driver for on-site production of green hydrogen via electrolysis. Therefore, cheap renewable electricity is an important prerequisite for the production of competitive green hydrogen. An important aspect in this context is that green hydrogen can be produced everywhere at almost every scale where low cost renewable resources are available in order to achieve competitiveness. In addition, green hydrogen could also be produced on site where it is needed to reduce shipping costs. To reduce costs, green hydrogen producers want to have high efficiency for the process, which means not just having the most efficient electrolyser, but importantly having long periods of sunshine and/or wind to produce the green energy needed for running the electrolysers and producing pure water form waste water or seawater for the electrolysis. Concepts like the European North Sea Hydrogen Hub which plans to utilize wind power over a large area of the North Sea for green hydrogen production is another concept to compensate intermittency in wind power and to provide low cost renewable energy.

Nevertheless, cheap electricity, while important, is not the only parameter for low cost green hydrogen production. The reductions in the cost of electrolysers is another parameter, because electrolyser cost is the second largest cost component of green hydrogen production. In order to bring this cost component down, strategies ranging from increasing efficiency of electrolyser through new electrolyser stack and system design, their construction, and replacing expensive materials by cheaper solutions such as the catalyst in polymer electrolyte membrane (PEM). It is expected that increasing the electrolyser size from about 1 MW to multi module 20 MW electrolyser could almost halve the cost [37].

In addition to electrolyser design, increasing stack and module production and an automated production of standardised stacks and modules can achieve a step-change in cost reduction. At lower manufacture rates, the stack is about 45% of the total cost, but at higher production rates, it can go down to 30%. It is estimated that production of 1000 units of PEM electrolysers with 1 MW capacity per year, an almost 50% cost reduction in stack manufacturing, can be achieved [38].

2.4. Carbon intensity of hydrogen production

One of the important questions regarding the use of green hydrogen is, whether related greenhouse gas emissions justify the significant investments in renewable energy generation, or whether conventional production of hydrogen using fossil fuels are equally valid.

The use of hydrogen in fuel cells only produces water vapor as emission. Used in internal combustion engines of cars, emission may also contain NOx [39] which needs to be removed from the emission. However, considering the green-house gas emission during production of the various types of hydrogen, the amount of this varies significantly. Hydrogen produced via electrolysis of water (green and pink hydrogen) does not cause any direct green-house gas emissions. However, if fossil fuels are used as source for hydrogen production, the direct emissions are with about 20 kg CO2 per kg of hydrogen in case of coal and about 10 kg CO2 per kg of hydrogen in case of natural gas [40].

A case can be made for hydrogen production combined with carbon capture and storage, like blue hydrogen. In this case, the direct emission are present, but not released into the atmosphere. There is much debate about the feasibility for carbon capture and storage applied to very large quantities of CO2 emissions, as expected from the production of hydrogen, but in general this technology has been applied for many years e.g., to maintain pressure in the geological fossil fuel reservoirs during extraction of natural gas and oil [41]. However, while hydrogen from electrolysis of water can be produced everywhere where sufficient amounts of water and electricity are available, the production of hydrogen from fossil fuels with carbon capture and storage can be expected to be confined to the areas where natural gas is extracted and CO2 can be pumped underground and significant emissions and costs can occur through extended supply lines.

Nevertheless, green hydrogen has a carbon foot print, but a very low one compared to grey, or black hydrogen. Green hydrogen produced from solar PV electricity has been calculated to have a carbon footprint of 1.7 to 4.4 kg CO2 per kg of hydrogen, which is comparable to blue hydrogen at the level of 60–90% of carbon capture and storage. However, the carbon footprint of green hydrogen is 85–95% lower than the carbon footprint of grey hydrogen. Produced from wind energy, the carbon footprint of green hydrogen is only 0.4 to 0.8 kg CO2 per kg of hydrogen, which is about 75% lower than that of blue hydrogen and 97% lower than that of grey hydrogen [42].

The comparison of the carbon footprint of the various types of hydrogen clearly shows that any sort of hydrogen from fossil fuels causes significant emissions. Therefore, only hydrogen from electrolysis is sufficiently emission free. Countries with sufficient penetration of nuclear power in their energy mix may focus on pink hydrogen, but all nations without nuclear power in their energy mix will most likely focus on green hydrogen [43,44].

3. Certifying green hydrogen

Certification of products to ensure the consumer that the product is what expected is an important tool for marketing and consumer acceptance. In regards to hydrogen, it is obvious that consumers who want green hydrogen for reducing their carbon food print expect they get green hydrogen. The establishment of a hydrogen Guarantee of Origin (GO), or certification scheme, is a priority action under Australia’s National Hydrogen Strategy. This scheme will be vital to give purchasers transparency as Australia and the world looks to facilitate clean hydrogen trade.

Hydrogen as an internationally traded commodity of major importance will require strict guarantee of origin (GO) certification which will prove how and where the hydrogen was produced. It will be crucial that in hydrogen trading countries the certification requirements and methodology for a hydrogen GO scheme will be consistent, transparent, and reliable. Such a hydrogen GO scheme will provide consumers with information that will enable them to choose the hydrogen product of their choice and give consumers assurance about the carbon footprint of the hydrogen used and eventually that of the product produced using hydrogen.

The scheme needs to be allowed to evolve over time, because new hydrogen production processes may evolve which needs to be included in a hydrogen GO scheme. Moreover, products based on hydrogen, such as ammonia, green steel, and green cement, need to be included in such a GO scheme or require their own GO scheme that reflects the source of hydrogen used for their production.

The methodology underpinning a hydrogen GO scheme will be of significance and it will be important to agree on an international standard for such a methodology, like the one developed by the International Partnership for Hydrogen and Fuel Cells in the Economy [45]. The underpinning methodology can also draw on the principles for carbon accounting presented in International Organization for Standardization (ISO) standards, which outlines the framework, requirements, regulations, and processes to assess the green house gas emissions associated with a given product [46].

The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Inventories also provide specific methods and emissions factors to support calculation of the GHG inventory for hydrogen [47].

It is obvious that a hydrogen GO scheme needs an international effort. Without a GO scheme consumers will be left in the dark about the carbon footprint of the hydrogen product that they use and eventually the carbon footprint of their product that bases on the hydrogen used.

Chemical signatures in the hydrogen product can be used as indicators of the origin and production process of hydrogen. While hydrogen produced from fossil fuels will most likely have impurities of methane, CO2, CO, and water, hydrogen produced via electrolysis of water will have impurities of mainly water. Impurities in gold hydrogen can vary depending on the geology of the area where it is mined, but it can be assumed that other natural gasses that occur in the Earth's crust like helium, argon, neon, and methane, may represent impurities in gold hydrogen. Common chemical analysis techniques like gas chromatography can easily be applied to detect impurities in hydrogen and provide data to identify the origin of the hydrogen product.

4. Applications

Apart from using green hydrogen for decarbonizing the generation of electric power, other major industrial manufacturing process and applications can be decarbonized by the use of green hydrogen, either directly to generate heat or for the production of source materials.

4.1. E-fuels

E-fuels are synthetic fuels, which are produced from the combination of green hydrogen and atmospheric CO2. e-fuels are considered to be carbon neutral [48]. Petrol, diesel and kerosene fuels are currently produced as e-fuels, but only in very small amounts. Similar to green hydrogen, high investments are considered necessary to scale up production of e-fuels and only the future will tell, whether these fuels will be able to be price competitive with green hydrogen, as they require an additional production step based on green hydrogen, and whether a sizable market will be available for the use of these fuels [48].

Beside fuels for mobility, e-fuels can be a significant contribution to the decarburization of plastic production. In this case, e-fuel, such as e-ethane or e-propane, can be used as a building block for plastic instead of ethane and propane formed from fossil fuels [49].

4.2. Green ammonia

In 2022, more than 150 million metric tons of ammonia were produced worldwide, mainly through steam reforming of methane to produce grey hydrogen and atmospheric nitrogen. Main products from ammonia are fertilizer and explosives. The use of green hydrogen for decarbonizing the production of ammonia will have a very significant effect on the reduction of the CO2 emissions from current ammonia production [50]. Green ammonia is also considered as a potential fuel for the maritime transport industry to replace fossil fuels [51].

4.3. Green steel

World steel production in 2022 was more than 1,830 million metric tons and is considered to be among the main sources of CO2 emissions through the use of coal fired blast furnaces in steel making. The use of green hydrogen instead of coal in the steel making process can significantly reduce the CO2 emissions from steel making [52]. Apart from green steel, the production other metals which are made by using coal fired blast furnaces, like copper, can also be decarbonized by the use of green hydrogen.

4.4. Mobility

The current discussion about the decarburization of mobility, especially car, trucks, and busses, is focused on three technologies: battery electric vehicle (BEV), fuel cell electric vehicle (FCEV) using hydrogen, and internal combustion engine (ICE) using hydrogen instead of petrol or diesel [53]. All three technologies have advantages and disadvantages (Table 3). While BEVs are considered to be the most efficient option, BEVs require considerable amounts of critical minerals, namely lithium, cobalt, and nickel for the battery, as long as no other battery designs are commercialized that do not need these materials and copper for the electric connections and especially electric motors. The recent report of the World Bank outlines that the demand for all four elements will be very significant in the future and will most likely outstrip current supply as long as new resources are developed and available for the market. The effect of this situation of the price of these critical minerals is not yet clear, but it is already forecasted that the price needs to be significantly higher to ensure investments for increasing supply.

In addition, ensuring secure supply lines is essential. FCEV also require higher amounts of cooper for the electric motors and fuel cells require catalysts to operate, which are currently very expensive platinum group elements. ICE do not require any of these critical elements apart from copper for the usual electric wiring which is equivalent to current petrol or diesel cars, but their lower efficiency causes higher hydrogen consumption.

Another advantage of ICE is that hydrogen for use in ICE can have a much lower level of purity, usually 98% or less, and is cheaper, compared to hydrogen used for fuel cells, usually 99.5%. This is due to the sensibility of the PEM membrane in the fuel cell on carbon dioxide and carbon monoxide [54].

4.5. Green hydrogen as energy storage medium

Green hydrogen is also considered as energy storage medium for excess electric energy produced by wind and solar power when it is not needed, e.g., during periods when solar power is produced in large quantities, but not fully used by the consumers, e.g., during mid-days. This concept is based on the idea that the excess electric energy can be stored in a chemical medium and used when needed or even transported to places where renewable energies are not abundant. In this context, green hydrogen replaces fixed battery installations for renewable electric energy storage. While this concept has potential, the overall loss of energy from transforming electric energy into green hydrogen via electrolysis and back is still of economic concern [55–58].

5. Hydrogen safety

Safe operations of hydrogen facilities and systems are essential and understanding the causes of incidents is important. Mechanical failure and human errors are the main reason for hydrogen release and leakage resulting in a containment loss and often fires. Hydrogen density, molecular weight, flammability range, flame temperature, combustion heat, and burning velocity are different from conventional gaseous fuels such as methane and hence careful protocols are required to ensure safe scaling of hydrogen in different sectors. Hydrogen safety aspects are linked to both material-related issues such as embrittlement and permeation and handling-related issues such as fire and explosion.

Hydrogen storage and pipelines are made of steel and metal and the exposure of them to hydrogen may cause mechanical failure in the long term and hydrogen leaks due to embrittlement, affecting the integrity of hydrogen assets. Other material safety aspects are permeability and blistering which should be carefully considered in designing hydrogen storages.

A hydrogen fire is characterized by high velocity and high temperature. Therefore, the National Fire Protection Association (NFPA) gives hydrogen the highest flammability rating of four [9]. A jet fire is the result of the immediate ignition of the released hydrogen. Whereas, the explosion of hydrogen air mixtures can occur when hydrogen is accumulated and then ignited. Both are critical for hydrogen transport and applications due to the high-pressure hydrogen storage tank [60]. Deflagration and detonation are two key phenomena associated with hydrogen fire and explosion [61, 62].

Deflagration can occur in closed or vented spaces and even in open spaces. Deflagration often starts from an initially quiescent hydrogen air, causing different flame acceleration effects. From the safety perspective, the most dangerous scenario is the deflagration-to-detonation transition process [61] which is usually followed by a stable detonation [63] associated with a supersonic compression wave with high energy release, high pressure and temperature increase, and related severe blast damage and burning [62].

Another serious safety issue arises from fast-filling of the tanks of hydrogen vehicles. High refueling rates and short refueling times are expected by consumers to reduce time spend for re-filling.

The expected increase in fuel cell cars, passenger cars, buses and trucks will surely draw close attention to this safety issue. The short refueling process of high pressure hydrogen results in compression effects which leads to a possibly significant temperature variation in the tanks and potential damage of the structural integrity of the tank over time or potentially catastrophic disintegration of the tank.

Proper management is essential to prevent the accidental release of hydrogen in production sites, storage systems, transmission, and refueling to avoid catastrophic fire and explosion consequences. Accidental releases of hydrogen can be reduced by applying standardized technology. Although hydrogen is used for many years, hydrogen vehicles or hydrogen stationary power generation are relatively new. Hence, for these systems, the development of hydrogen codes and standards is essential to increase the safety of operation. This can be only achieved through collaborations between industry, governments, and safety experts, and the involvement of national and international standards organizations. Several national and international organisations have already adopted adjustments to standards for hydrogen. The main bodies are ISO, the International Electro technical Commission (IEC), the National Fire Protection Association (NFPA), the American Society of Mechanical Engineers (ASME), the Compressed Gas Association (CGA), European Industrial Gases Association (EIGA) and International Maritime Dangerous Goods (IMDG). There are equivalent organizations in various countries such as British Standards in the UK, Japanese Standards Association, the American Society for Testing and Materials in the USA, CSA Standards in Canada and the USA, the National Institute of Standards and Technology in the USA, and Standards Australia. As an example, the IEC committees and ISO have provided guidelines on fuel cell technologies and electric road vehicles, to ensure the safety of hydrogen fuel cell technologies. NFPA enhanced the standards and codes for both gaseous and liquid hydrogen systems at consumer sites. ASME setup codes which are more relevant to the hydrogen pipelines. CGA Hydrogen Initiative has also addressed the challenges in hydrogen safety information and regulations, particularly for hydrogen mobility in the transport sector. EIGA provided updated guidelines for hydrogen production, hydrogen storage and handling, gas network, and hydrogen mobility, Despite this progresses, further efforts are essential to develop consistent safety training materials and guidelines as well as clear national and international regulations, codes, and standards to enable scaling green hydrogen.

6. Hydrogen storage

Large scale hydrogen storage will be a critical component for the supply of large amounts of hydrogen for entire industry sector and to balance supply and demand at a large scale. While small scale hydrogen storage, e.g., in the form of pressurized hydrogen or liquefied hydrogen, is an established technology, it can be expected that applying these technologies for large scale storage is economically problematic. For example, storing hydrogen at 100 bar requires about 1 kWh per kg of hydrogen, which is most likely economically not feasible for large scale storage [64]. In addition, due to the significant volume of 11 m2 per kg of hydrogen, storing large quantities of hydrogen at ambient pressure would require very large storage facilities which would also not practicable for large scale storage. Therefore, new concepts and methods need to be established [64].

Geological storage is seen to be one feasible option. Salt caverns or depleted oil or gas reservoirs are already explored as potential hydrogen storage options, because they are known to have the capacity to hold gas like methane and hydrogen. While salt caverns are commercially proven geo-rock for hydrogen storage, they have low-storage capacity compared to depleted gas reservoirs and are, therefore, more suitable for medium scale hydrogen storage [65, 66]. The costs for large scale hydrogen storage will affect the economics of the hydrogen industry. Therefore, low cost solutions are important.

The use of already known and available geological storage options are worthwhile to explore. However, since each storage location has its individual geology, each storage location has its own individual set of problems which need individual solutions and management protocol. It is obvious that geological storage will take time and investments to be established [65, 66].

7. Conclusions

Green hydrogen will play an important role in achieving carbon net-zero targets by 2050. This has been acknowledged by many nations and industry sectors. While the production process of green hydrogen via electrolysis is well established, significant efforts will be necessary for scaling up production of green hydrogen worldwide. Since water is the key ingredient for green hydrogen, the development of direct seawater electrolysis is most likely the most important aspect in this context and further efforts into commercializing current developments and reducing the cost of direct seawater electrolysis is necessary.

The cost of green hydrogen is still higher than that of conventional produced hydrogen, but scaling up of green hydrogen production, potential significant carbon pricing and general future reduction I the production of fossil fuel will bring the price of green hydrogen down to a level where it is well placed to compete with non-green hydrogen. Often reiterated comments that green hydrogen is not and will never be competitive appear to ignore lessons from the past like the rise of solar and wind power and the related fall of the costs for solar and wind power and the power of consumers who may demand net-zero standards.

It will be necessary to established robust guarantees of origin legislations for hydrogen. Such legislated management protocols for the hydrogen industry will ensure consumers that they use hydrogen with the lowest carbon footprint if they wish to do so. Such legislations combined with consumer laws will be a robust measure to safeguard this.

Safe production of hydrogen, operation of hydrogen technology equipment, and storage will play an important role not only at industrial scale, but also at small scale and even household level. Proper worldwide accepted and implemented standards and safety management protocols for using hydrogen for the various new applications, their designs, and related hydrogen leak warning devices and sensors are essential components for safe operation of hydrogen.

Besides being used for generating electric and thermal power, the versatility of hydrogen for applications in many industrial processes like steel making and many organic chemicals and for fuelling cars, trucks and even planes will make it an indispensable energy carrier for a decarbonized society in the future.

Large scale hydrogen storage is still in its infancy, but will be an important component of the hydrogen production, trade and management of demand and supply variations. Today's hydrogen storage technologies are well established, but seem commercially not feasible for large scale storage.

Geological storage of hydrogen is a step in the right direction but still faces problems that need answers

8. References

1. Global hydrogen review 2022. Available from: https://www.iea.org/reports/global-hydrogenreview-2022.
2. Gold hydrogen natural hydrogen exploration. Available from: https://www.energymining.sa.gov.au/industry/energy-resources/regulation/projects-of-publicinterest/
3. Natural-hydrogen-exploration/gold-hydrogen-natural-hydrogen-exploration.
4. Guban D, Muritala IK, Roeb M, et al. (2020) Assessment of sustainable high temperature hydrogen production technologies. Int J Hydrogen Energy 45: 26156–26165. https://doi.org/10.1016/j.ijhydene.2019.08.145
5. Ursua A, Gandia LM, Sanchis P (2012) Hydrogen production from water electrolysis: Current status and future trends. Proc IEEE 100: 410–426.
6. Dincer I (2012) Green methods for hydrogen production. Int J Hydrogen Energy 37: 1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173
7. Balat M (2008) Potential importance of hydrogen as a future solution to environmental and transportation problems. Int J Hydrogen Energy 33: 4013–4029. https://doi.org/10.1016/j.ijhydene.2008.05.047
8. Moçoteguy P, Brisse A (2013) A review and comprehensive analysis of degradation mechanisms of solid oxide electrolysis cells. Int J Hydrogen Energy 38: 15887–15902. https://doi.org/10.1016/j.ijhydene.2013.09.045
9. Pinsky R, Sabharwall P, Hartvigsen J, et al. (2020) Comparative review of hydrogen production technologies for nuclear hybrid energy systems. Progress Nuclear Energy 123: 103317. https://doi.org/10.1016/j.pnucene.2020.103317
10. Khalili M, Karimian Bahnamiri F, Mehrpooya M (2021) An integrated process configuration of solid oxide fuel/electrolyzer cells (SOFC-SOEC) and solar organic Rankine cycle (ORC) for cogeneration applications. Int J Energy Res 45: 11018–11040. https://doi.org/10.1002/er.6587
11. Phillips R, Edwards A, Rome B, et al. (2017) Minimising the ohmic resistance of an alkaline electrolysis cell through effective cell design. Int J Hydrogen Energy 42: 23986–23994. https://doi.org/10.1016/j.ijhydene.2017.07.184
12. Wirkert FJ, Roth J, Jagalski S, et al. (2020) A modular design approach for PEM electrolyser systems with homogeneous operation conditions and highly efficient heat management. Int J Hydrogen Energy 45: 1226–1235. https://doi.org/10.1016/j.ijhydene.2019.03.185

13. Carmo M, Keeley GP, Holtz D, et al. (2019) PEM water electrolysis: Innovative approaches towards catalyst separation, recovery and recycling. Int J Hydrogen Energy 44: 3450–3455. https://doi.org/10.1016/j.ijhydene.2018.12.030
14. Kumar S, Himabindu V (2019) Hydrogen production by PEM water electrolysis—A review. Mate Sci Energy Technol 2: 442–454. https://doi.org/10.1016/j.mset.2019.03.002
15. Kim J, Jun A, Gwon O, et al. (2018) Hybrid-solid oxide electrolysis cell: A new strategy for efficient hydrogen production. Nano Energy 44: 121–126. https://doi.org/10.1016/j.nanoen.2017.11.074
16. Schnuelle C, Thoeming J, Wassermann T, et al. (2019) Socio-technical-economic assessment of power-to-X: Potentials and limitations for an integration into the German energy system. Energy Res Social Sci 51: 187–197. https://doi.org/10.1016/j.erss.2019.01.017
17. Buttler A, Spliethoff H (2018) Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renewable Sustainable Energy Rev 82: 2440–2454. https://doi.org/10.1016/j.rser.2017.09.003
18. Ganley JC (2009) High temperature and pressure alkaline electrolysis. Int J Hydrogen Energy 34: 3604–3611. https://doi.org/10.1016/j.ijhydene.2009.02.083
19. Badea G, Naghiu GS, Giurca I, et al. (2017) Hydrogen production using solar energy-technical analysis. Energy Proc 112: 418–425. https://doi.org/10.1016/j.egypro.2017.03.1097
20. Laguna-Bercero MA (2012) Recent advances in high temperature electrolysis using solid oxide fuel cells: A review. J Power Sources 203: 4–16. https://doi.org/10.1016/j.jpowsour.2011.12.019
21. Nechache A, Hody S (2021) Alternative and innovative solid oxide electrolysis cell materials: A short review. Renewable Sustainable Energy Rev 149: 111322. https://doi.org/10.1016/j.rser.2021.111322
22. Todd D, Schwager M, Mérida W (2014) Thermodynamics of high-temperature, high-pressure water electrolysis. J Power Sources 269: 424–429. https://doi.org/10.1016/j.jpowsour.2014.06.144
23. Fujiwara S, Kasai S, Yamauchi H, et al. (2008) Hydrogen production by high temperature electrolysis with nuclear reactor. Progress Nuclear Energy 50: 422–246. https://doi.org/10.1016/j.pnucene.2007.11.025
24. Li Q, Zheng Y, Guan W, et al. (2014) Achieving high-efficiency hydrogen production using planar solid-oxide electrolysis stacks. Int J Hydrogen Energy 39: 10833–10842. https://doi.org/10.1016/j.ijhydene.2014.05.070
25. Ni M, Leung MK, Sumathy K, et al. (2006) Potential of renewable hydrogen production for energy supply in Hong Kong. Int J Hydrogen Energy 31: 1401–1412. https://doi.org/10.1016/j.ijhydene.2005.11.005
26. Dresp S, Dionigi F, Klingenhof M, et al. (2019) Direct electrolytic splitting of seawater: Opportunities and challenges. ACS Energy Lett 4: 933–942. https://doi.org/10.1021/acsenergylett.9b00220
27. Khan M, Al-Attas T, Roy S, et al. (2021) Seawater electrolysis for hydrogen production: A solution looking for a problem? Energy Environ Sci 14: 4831–4839. https://doi.org/10.1039/D1EE00870F
28. Peterson D, Vickers J, Desantis D (2019) DOE hydrogen and fuel cells program record: Hydrogen production cost from PEM electrolysis, national renewable energy laboratory. Available from: https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf.
29. Guo J, Zheng Y, Hu Z, et al. (2023) Direct seawater electrolysis by adjusting the local reaction environment of a catalyst. Nat Energy 8: 1–9. https://doi.org/10.1038/s41560-023-01195-x

30. Australia's big clean energy build hits record highs: Clean Energy Australia report (2023). Available from: https://www.cleanenergycouncil.org.au/news/australias-big-clean-energy-buildhits-record-highs-cleanenergyaustraliareport#:~:text=%E2%80%9CLarge%2Dscale%20clean%20energy%20investment,data%20collection%20began%20in%202017.
31. Cosmos Magazine (2022) Australia to light the way with industrial-scale power. Available from: https://cosmosmagazine.com/technology/energy/pilbara-energy-hub/.
32. E. ON (2022) Fortescue future industries and E. ON partner on journey to become Europe's largest green renewable hydrogen supplier and distributer. Available from: https://www.eon.com/en/about-us/media/press-release/2022/2022-03-29-fortescue-futureindustries- and-eon-partnership.html.
33. Mohammed-Ibrahim J, Moussab H (2020) Recent advances on hydrogen production through seawater electrolysis. Mater Sci Energy Technol 3: 780–807. https://doi.org/10.1016/Jmset.2020.09.005
34. Guo J, Zheng Y, Hu Z, et al. (2023) Direct seawater electrolysis by adjusting the local reaction environment of a catalyst. Nat Energy 8: 264–272. https://doi.org/10.1038/s41560-023-01195-x
35. Chen Z, Wei W, Song L, et al. (2022) Hybrid water electrolysis: A new sustainable avenue for energy-saving hydrogen production. Sustainable Horiz 1: 100002. https://doi.org/10.1016/j.horiz.2021.100002
36. Freund S, Sanchez D (2022) Green hydrogen market and growth. Machinery Energy Syst Hydrogen Economy, 605–635. https://doi.org/10.1016/B978-0-323-90394-3.00001-1
37. Infolink Consulting (2022) Australia green hydrogen: production costs to drop 37% by 2030. Available from: https://www.infolink-group.com/energy-article/green-hydrogen-costs-inaustralia-to-reduce-37-by-2030.
38. IRENA (2020) Green Hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 ℃ climate goal. Int Renewable Energy Agency, Abu Dhabi.
39. Kampker A, Heimes H, Kehrer M, et al. (2022) Fuel cell system production cost modelling and analysis. Energy Rep 9: 248–255. https://doi.org/10.1016/Jegyr.2022.10.364
40. Heffel JW (2003) NOx emission and performance data for a hydrogen fueled internal combustion engine at 1500 rpm using exhaust gas recirculation. Int J Hydrogen Energy 28: 901–908. https://doi.org/10.1016/S0360-3199(02)00157-X
41. Internet Energy Agency (2022) Global hydrogen review 2022. Int Energy Agency, IEA Publications.
42. Rezk MG, Foroozesh J, Zivar D, et al. (2019) CO2 storage potential during CO2 enhanced oil recovery in sandstone reservoirs. J Natural Gas Sci Eng 66: 233–243. https://doi.org/10.1016/j.jngse.2019.04.002
43. Valente A, Iribarren D, Dufour J (2020) Prospective carbon footprint comparison of hydrogen options. Sci Total Environ 728: 138212. https://doi.org/10.1016/j.scitotenv.2020.138212
44. de Kleijne K, de Coninck H, van Zelm R, et al. (2022) The many greenhouse gas footprints of green hydrogen. Sustainable Energy Fuels 6: 4383–4387. https://doi.org/10.1039/D2SE00444E
45. Howarth RW, Jacobson MZ (2021) How green is blue hydrogen? Energy Sci Eng 9: 1673–1945. https://doi.org/10.1002/ese3.956
46. Hydrogen Certification 101 (2023) International partnership for hydrogen and fuel cells in the economy. 2022, IPHE.net.
47. ISO 14064-2 (2019) Greenhouse gases—Part 2: Specification with guidance at the project level for

quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. Available from: https://www.iso.org/obp/ui/#iso:std:iso:14064:-2:ed-2:v1:en.

48. IPCC (2019) 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Available from: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipccguidelines- for-national-greenhouse-gas-inventories/.
49. Yugo M, Soler A (2019) A look into the role of e-fuels in the transport system in Europe (2030–2050), (literature review). Available from: https://www.concawe.eu/wp-content/uploads/E-fuelsarticle.pdf.
50. Zhao C, Sun J, Zhang Y (2022) A study of the drivers of decarbonization in the plastics supply chain in the post-COVID-19 era. Sustainability 14: 15858. https://doi.org/10.3390/su142315858
51. IEA (2021) Ammonia technology roadmap. Available from: https://www.iea.org/reports/ammonia-technology-roadmap, License: CC BY 4.0.
52. Global Maritime Forum (2022) Ammonia as a shipping fuel. Available from: https://www.globalmaritimeforum.org/news/ammonia-as-a-shipping-fuel.
53. Griffin PW, Hammond GP (2021) The prospects for 'green steel' making in a net-zero economy: A UK perspective. Global Transitions 3: 72–86. https://doi.org/10.1016/j.glt.2021.03.001
54. Demartini M, Ferrari M, Govindan K, et al. (2023) The transition to electric vehicles and a net zero economy: A model based on circular economy, stakeholder theory, and system thinking approach. J Cleaner Product 40: 137031. https://doi.org/10.1016/j.jclepro.2023.137031
55. Staffell I, Scamman D, Velazquez Abad A, et al. (2019) The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 12: 463–491. https://doi.org/10.1039/C8EE01157E
56. Razmi AR, Sharifi S, Gholamian E, et al. (2023) Green hydrogen—Future grid-scale energy storage solutions. Mech Chem Technol Principles 15: 573–619. https://doi.org/10.1016/B978-0- 323-90786-6.00006-6
57. Razmi AR, Alirahmi SM, Nabat MH, et al. (2022) A green hydrogen energy storage concept based on parabolic trough collector and proton exchange membrane electrolyzer/fuel cell: Thermodynamic and exergoeconomic analyses with multi-objective optimization. Int J Hydrogen Energy 47: 26468–26489. https://doi.org/10.1016/j.ijhydene.2022.03.021
58. Alirahmi SM, Razmi AR, Arabkoohsar A (2021) Comprehensive assessment and multi-objective optimization of a green concept based on a combination of hydrogen and compressed air energy storage (CAES) systems. Renewable Sustainable Energy Rev 142: 110850. https://doi.org/10.1016/j.rser.2021.110850
59. Urs RR, Chadly A, Sumaiti AA, et al. (2023) Techno-economic analysis of green hydrogen as an energy-storage medium for commercial buildings. Clean Energy 7: 84–98. https://doi.org/10.1093/ce/zkac083
60. National Fire Protection Association (2007) NFPA 68: Standard on explosion protection by deflagration venting.
61. Folkson R (2014) Alternative fuels and advanced vehicle technologies for improved environmental performance: Towards zero carbon transportation. 2nd Eds. https://doi.org/10.1016/c2020-0-02395-9
62. Zhang B, Liu H, Wang C (2017) On the detonation propagation behavior in hydrogen-oxygen mixture under the effect of spiral obstacles. Int J Hydrogen Energy 42: 21392–21402, https://doi.org/10.1016/j.ijhydene.2017.06.201
63. Ng HD, Lee JH (2008) Comments on explosion problems for hydrogen safety. J Loss Prev Process

Ind 21: 136–146. https://doi.org/10.1016/j.jlp.2007.06.001
64. Teng H, Tian C, Zhang Y, et al. (2021) Morphology of oblique detonation waves in a stoichiometric hydrogen-air mixture. J Fluid Mech 913: A1. https://doi.org/10.1017/jfm.2020.1131
65. Andersson J, Grönkvist S (2019) Large-scale storage of hydrogen. Int J Hydrogen Energy 44: 11901–11919. https://doi.org/10.1016/Jijhydene.2019.03.063
66. Muhammed NS, Haq B, Al Shehri D, et al. (2022) A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. Energy Rep 8: 461–499. https://doi.org/10.1016/Jegyr.2021.12.002
67. Aftab A, Hassanpouryouzband A, Xie Q, et al. (2022) Toward a fundamental understanding of geological hydrogen storage. Eng Chem Res 61: 3233–3253. https://doi.org/10.1021/acs.iecr.1c04380