Hydrogen as Energy Carrier

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Introduction

Although South Africa lags European countries in terms of electric vehicle (EV) deployment, there are currently well over a thousand EVs on our roads. It is expected that the rise in numbers of EVs will accelerate in the coming years. In fact, the automotive industry's goal is for 20% of all road vehicles to be EVs by 2030 and 35% of new vehicles to be EVs (Tyilo, 2019).

EVs can certainly help reduce carbon dioxide (CO_2) emissions to the atmosphere, provided that the electricity they consume comes from renewable sources, i.e. wind, solar, hydroelectric or geothermal sources. Whilst EVs are excellent for short distances, range limitations, and the time required to recharge the batteries, reduce their practicality over long distances. To overcome the problem, charging stations are being installed along major routes in South Africa (Cokayne, 2019), but even with fast chargers, it still takes approximately 72 minutes to achieve an 80% charge.

Fortunately, there are other energy carriers, such as hydrogen, which are both clean and convenient. Hydrogen is the most abundant gas in the universe, and the source of the energy we receive from the sun. The sun is essentially a giant ball of hydrogen and helium gases. In the fusion process in the sun, hydrogen nuclei combine to form one helium atom, releasing energy as radiation. Hydrogen is found only in compound form on Earth: combined with oxygen, it is water (H_2O); combined with carbon, it forms organic compounds such as natural gas, coal, and petroleum. Hydrogen is also one of the most abundant elements in the Earth's crust. Hydrogen, like electricity, is regarded as an energy carrier, not an energy source, because hydrogen as a gas (H_2) doesn't exist naturally on Earth. It requires much energy to produce hydrogen gas, but in this form, it can deliver or store tremendous amounts of energy.

In this article, we share some thoughts about a potential future hydrogen economy, discuss the different production routes for hydrogen, consider logistic implications of hydrogen storage and distribution, and describe some of the applications of hydrogen, and particularly transport applications.

Hydrogen economy

The term ‘hydrogen economy’ describes the vision of utilising hydrogen as a low carbon alternative energy carrier to replace traditional fossil fuels for transportation and heat. When produced from renewable energy sources such as solar or wind, hydrogen has zero CO_2 emissions at the point of use. Hydrogen burns readily with oxygen, releasing considerable amounts of energy as heat, and producing only water as exhaust, as illustrated by the reaction:

$$2\ H_2 + 0_2 \rightarrow 2\ H_20 + \text{heat}$$

According to Potier and Chung (2019), “[c]lean hydrogen energy - that is, hydrogen produced from renewable and low carbon sources and/or produced with a low greenhouse gas footprint - can, as part of our primary world energy mix, help us achieve the Paris [Climate] Agreement goals while creating jobs and bolstering economies”.

Toyota (2019) presented their vision of a hydrogen economy at the launch of the hydrogen-fueled Toyota Mirai, a fuel cell vehicle (FCV), in 2019. Toyota’s vision of the hydrogen economy is shown in Figure 1.

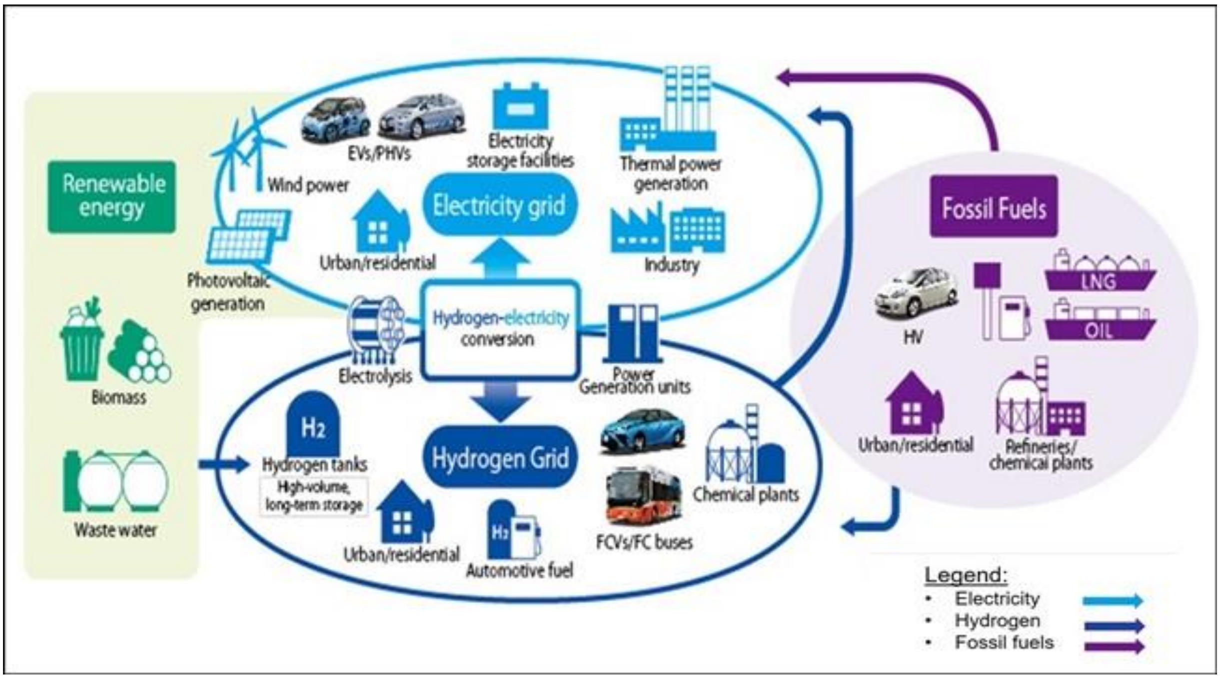

Figure 1: Sustainable hydrogen energy based society (Toyota, 2019)

Several interesting observations can be made regarding Toyota’s vision for a hydrogen economy, namely:

- Hydrogen, electricity and fossil fuels play an important role, although the importance of fossil fuel for transport is much smaller than at present;

- Electricity can be used to produce hydrogen via electrolysis, and electric power can by generated from hydrogen, and other fossil fuels;
- Motor vehicles will be electric powered (EV), electric powered with a small hydrocarbon fueled engine to charge the batteries (hybrid vehicles or HV), plug-in hybrid vehicles (PHV), or hydrogen fuel cell powered vehicles driven by electric motors (FCV);
- Natural gas and petroleum will still be used as fuels and to feed the chemical industries, but coal does not form part of the fossil fuel mix;
- Nuclear energy is not included in the diagram and the deduction is made that nuclear energy is not considered to be a primary energy source for the future; and
- No mention is made of carbon capture and storage (CCS) for fuels from carbon-based (fossil) sources, although this will probably be required.

The transition to a hydrogen economy would require trillions of dollars of investment in new infrastructure to produce, transport, store and deliver hydrogen to end users. The process could take several decades, because of the slow turnover of the existing stock of capital equipment that either makes or uses energy, as well as the sheer capacity that would need to be built. A hydrogen economy can become a reality if clean hydrogen can be produced, stored and transported on a technology proven and commercially viable scale.

Hydrogen production

Opening remarks

Hydrogen can be produced from fossil fuels, biomass, water, or from a mix of these resources. The annual global dedicated hydrogen production is around 70 million tons (IEA, 2019) with the largest consumers being ammonia production at 62,4%, oil refining at 24,3% and methanol production at 8,7% (Bhandari, Trudewind, & Zap, 2012). The use of hydrogen as an energy carrier is negligible.

Hydrogen is generally produced by steam or autothermal reforming of natural gas at consumer sites where large quantities of hydrogen are required. Globally, about 68% of hydrogen production comes from natural gas, 16% from oil, 11% from coal, and only 5% from electricity (Adolf et al, 2017). It is estimated that only a small fraction of the electricity used to produce hydrogen from water is from renewable sources.

In this section we'll discuss some options to produce hydrogen. Hydrogen production technologies are shown in Figure 2, starting with different primary energy sources, and via several energy carriers. As stated above, thermochemical processes, like steam and autothermal reforming of natural gas, predominate.

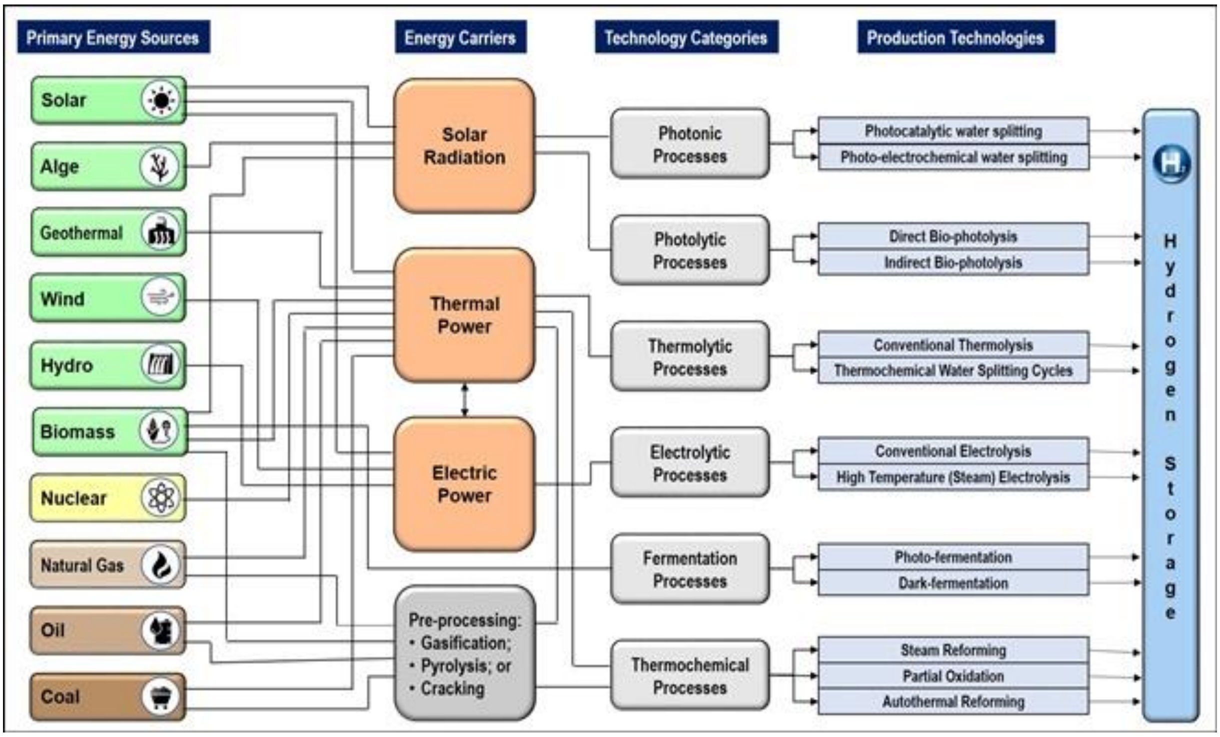

Figure 2: Hydrogen production from different energy sources

Each of the production technologies is discussed in more detail below.

Photonic processes

Photonic processes essentially use sunlight as an energy source to split the water molecule using either photocatalytic or photo-electrochemical means. The conversion from water to hydrogen requires a flow of free electrons, generated by the light source, that acts as an electric current to split the water molecule. Photocatalysis uses a direct heterogeneous catalyst and the photo-electrochemical process employs an electrochemical cell in which at least one of the electrodes is made from photoactive material such as titanium dioxide.

Photonic processes are not yet fully developed or commercially proven.

Photolytic processes

These processes include both direct and indirect bio-photolysis, which is the production of hydrogen from water by the action of light on a biochemical compound such as green microalgae or cyanobacteria. These light-sensitive microorganisms are used as biological converters in a specially designed photo-bioreactor. The advantage of bio-photolysis is the ability to produce hydrogen from water in an aqueous environment at standard temperature and pressure.

Photolytic processes are not yet fully developed or commercially proven.

Thermolytic processes

Water thermolysis is the single step thermal dissociation of water requiring temperatures above 2000 K. At 3000K and 1 bar, the degree of dissociation is 64%. The high temperature heat can be supplied by concentrated solar power or from the waste heat of nuclear power reactions. The main challenge of this production method is the separation of hydrogen and oxygen. Membranes can potentially be used below 2500 K and require the rapid cooling of the product stream.

Thermochemical water splitting cycles uses high temperatures and chemical reactions to produce hydrogen from water. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. This process route has a more reasonable temperature requirement range of 600 to 1200 K and has no need for oxygen/hydrogen separation membranes.

Electrolytic processes

Electrolysis is the process of breaking down a feedstock, in this case water, into hydrogen and oxygen by electricity. The electrolyser consists of a direct current source of electricity and two noble metal electrodes, which are separated by an electrolyte, as illustrated in Figure 3. Also shown in Figure 3 is the reverse reaction of electrolysis, namely the hydrogen fuel cell, where hydrogen and oxygen are reacted to produce electricity.

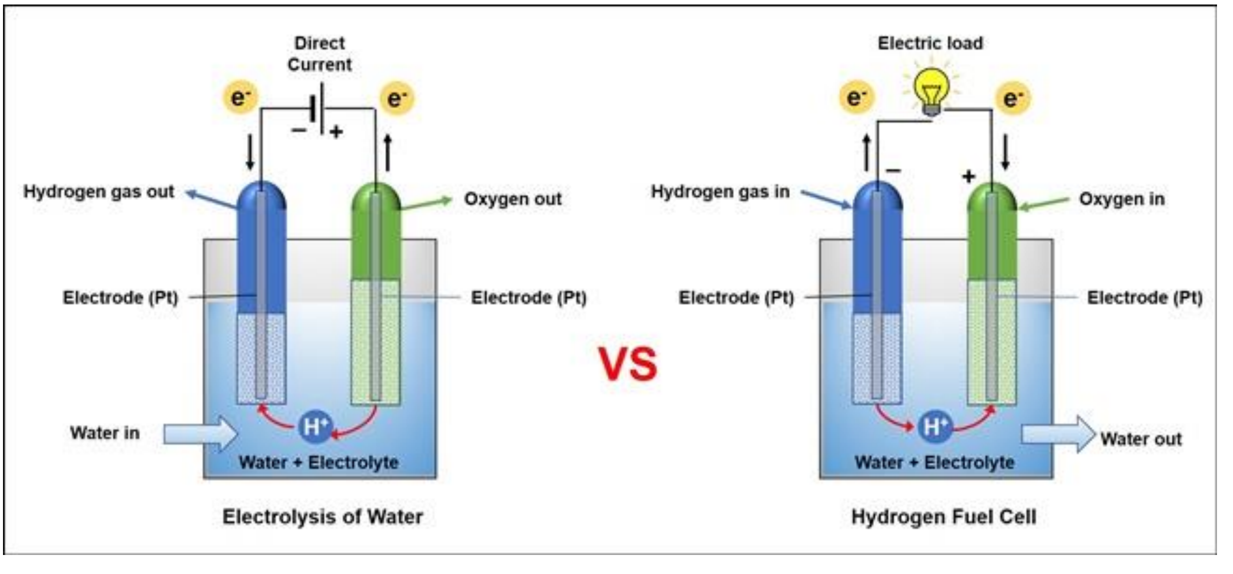

Figure 3: Principles of the electrolysis of water and the hydrogen fuel cell (Adapted from Minnehan & Pratt, 2017)

Noble metal electrodes, typically platinum, function as a catalyst to increase current density and rate of electrolysis reactions. Electrolysis can be carried out at room temperature (conventional electrolysis), or at higher temperature (1000 K to 1300 K) where steam is initially produced and then is dissociated to hydrogen and oxygen (high temperature electrolysis). The higher temperatures result in increased efficiency of up to 80%. Also, water is converted to steam using thermal energy and hence the electrical energy need is lower than that of conventional electrolysis.

Several types of electrolysers are available and are differentiated by the specific electrolyte used, and include:

- Alkaline electrolysers (AE);
- Proton exchange membrane (PEM) electrolysers;
- Solid polymer electrolyte (SPE) electrolysers;
- Solid oxide electrolysis cells (SOEC); and
- Anion exchange membrane (AEM) electrolysers.

Fermentation processes

Fermentation processes fall into two categories: Photo-fermentation and Dark-fermentation. Biochemical energy, which is stored in organic matter, can be used by living organisms to extract hydrogen from water in the presence or absence of light. Photo-fermentation (with light) utilises carbon substrates such as organic acids as electron donors and hence is suited for hydrogen production from waste streams containing organic acids.

Dark-fermentation (in the absence of light) produces hydrogen using anaerobic bacteria on carbohydrate-rich substrates, mainly glucose. This process is cheaper than photo-fermentation as the process does not require solar input (the bioreactors are simpler). Dark-fermentation can be integrated into wastewater treatment systems to produce hydrogen. Acetate produced in dark-fermentation can be oxidised by photosynthetic bacteria to produce more hydrogen, hence a maximum yield of hydrogen can be achieved by integrating dark- and photo-fermentation processes.

Thermochemical processes

The most established and proven processes for bulk hydrogen production entails the conversion of methane (from natural gas) to hydrogen, carbon monoxide (CO), carbon dioxide (CO_2), and water vapour via reforming. Based on the nature of the oxidant used in the reforming process, three different types of reforming can be identified, namely Steam Methane Reforming (SMR), Partial Oxidation (POx) or Autothermal Reforming (ATR) .

Pure water vapour is used as the oxidant for SMR. The reaction requires the introduction of heat, often supplied from the combustion of some of the methane feed-gas. The process typically occurs at temperatures of 700 to 900°C and pressures of 3 to 25 bar. The product gas contains approximately 12% CO, which can be further converted to CO_2 and H_2 through the water-gas shift reaction. SMR is the least expensive and most used process to produce hydrogen.

Oxygen or air is used as the oxidant for POx. If ambient air is used as an oxidant, the product gas also contains nitrogen. POx of natural gas is the process whereby hydrogen is produced through the partial combustion of methane (CH_4) with oxygen to yield CO and H_2. In this process, heat is produced in an exothermic reaction, and hence a more compact design is possible as there is no need for any external heating of the reactor. Partial oxidation has the benefit of not requiring a catalyst and is more sulphur tolerant.

The ATR process is a combination of SMR and POx and operates with a mixture of air and water vapour as the oxidant. The ratio of the two oxidants is adjusted so that no heat needs to be introduced or discharged. The outlet temperature from the reactor is in the range of 950 to 1100 °C, and the gas pressure can be as high as 100 bar. Again, the CO produced is converted to H_2 through the water-gas shift reaction.

Effectively all carbon entering the processes, described above, gets converted to CO_2. Large scale hydrogen production using these processes would therefore require the establishment of carbon capture and storage (CCS) infrastructure in order to be environmentally sustainable. CCS necessitates the proximity of suitable underground geological structures for the storage of CO_2.

Gasification of coal or biomass, followed by a water-gas shift reactor to increase the hydrogen yield, is also a viable route to hydrogen. Gasification of coal results in higher CO_2 emissions and would need CCS infrastructure. The raw material costs are lower for this process route, but the capital cost is higher (due to gasification and air separation capital).

Storage and distribution

Hydrogen is the lightest and simplest element in existence: a hydrogen atom contains only one proton and one electron. Hydrogen also exhibits the highest heating value per mass of all chemical fuels, and is environmentally friendly. Hydrogen is a combustible gas and can form explosive mixtures with air, although it is not explosive by itself. Its most obvious safety-related feature is its high flammability and the broad ignition limits in hydrogen-air mixtures from 4 to 77 %. If pure hydrogen is brought together with air/oxygen and an ignition source, it burns almost invisibly.

One difficulty with hydrogen as an energy carrier is its low critical temperature of 33 K (-240 ℃), i.e. hydrogen is a gas at ambient temperature. The low density of hydrogen also has an impact on its transport. Under standard conditions (1.013 bar and 0°C), hydrogen has a density of 0.0899 kg/m^3. If hydrogen is compressed to 200 bar, the density at 0°C increases to 15.6 kg H_2/m^3, and at 500 bar it would reach 33 kg H_2/m^3.

Finding a cost-effective solution to the hydrogen storage problem is considered by many to be the foremost challenge for the hydrogen economy.

There are a few different approaches for hydrogen transportation and storage. Hydrogen can be stored as a compressed gas in high pressure tanks, as a liquid in cryogenic tanks (at 20 K) or as a pressurised liquid at slightly higher temperatures. These methods are established technologies with several limitations, the most important being their energy intensive character. Hydrogen can also be stored in solid state compounds such as metal hydrides. Hydrogen storage in metal hydrides is considered one of the most attractive methods because metal hydrides contain the highest volumetric density of hydrogen. Hydrides reduce the risk factors of gaseous or liquid hydrogen. The metal hydrides also provide a safe method for fuel storage in hydrogen-powered vehicles. Light metals (Li, Mg, B, Al) can combine with hydrogen to form a large variety of metal-hydrogen complexes. $LiBH_4$ is a complex hydride which consists of 18% mass of hydrogen.

Today, the transport of compressed gaseous or liquid hydrogen by lorry and of compressed gaseous hydrogen by pipeline to selected locations are the main transport options used commercially. A pipeline network could be the best option for large scale use of hydrogen, but requires a high level of initial investment. Local, regional and transregional networks are a possibility. Worldwide there are already more than 4500 km of hydrogen pipelines.

Blending hydrogen into natural gas pipeline networks has also been proposed as a means of delivering pure hydrogen to markets, using separation and purification technologies downstream to extract hydrogen close to the point of end use.

Applications of hydrogen

Opening remarks

Present and potential future applications of hydrogen can be grouped in three main categories as illustrated in Figure 4, namely:

- Power and heat generation;
- Industry feedstock; and
- Passenger/goods transport.

Each of these is discussed in more detail below.

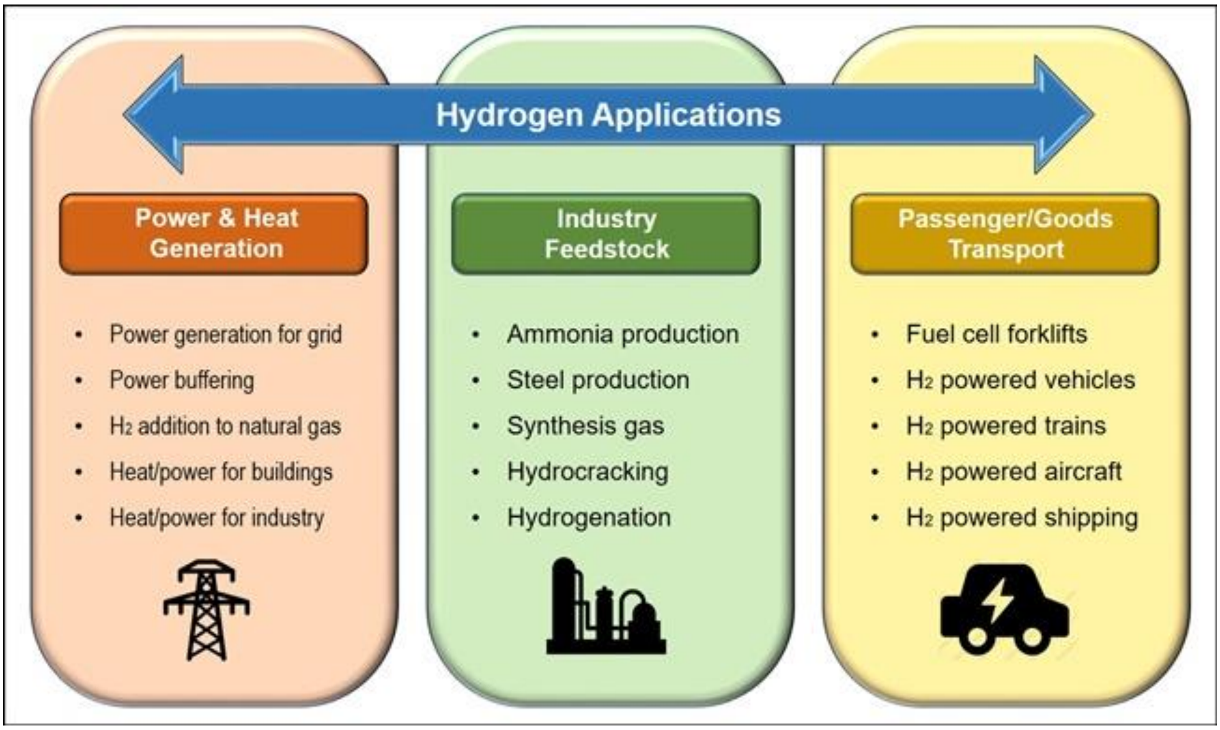

Figure 4: Present and future hydrogen applications

Power & heat generation

In power generation, hydrogen is one of the leading options for storing renewable energy, and can help to buffer electricity networks which depend on renewable energy. When additional electric power is required, hydrogen can be converted to electricity by fuel cell, or by using gas fired engines for power generation. Power so produced can be fed to the power grid.

Hydrogen can be used in its pure form or blended in with natural gas. Blending it in with natural gas has the advantage that existing gas pipeline networks can be used to transport the hydrogen. Pure or blended hydrogen can be used in buildings and in industry for heat and power generation, with the highest potential in multifamily and commercial buildings. Longer-term prospects could include the direct use of hydrogen in hydrogen boilers or fuel cells, provided a pure hydrogen pipeline is available.

Industry feedstock

Hydrogen is predominantly used today as a feedstock in industrial applications like ammonia production, steel production, synthesis gas for fuel production, methanol production and for hydrocracking and hydrogenation processes in oil refining. Currently, most, if not all, of this hydrogen is supplied using fossil fuels, so there is significant potential for emissions reductions from clean hydrogen.

Various industrial gases play a vital role in producing high quality flat glass. The most common are hydrogen and nitrogen for the tin bath and oxygen in case of oxy-fired furnaces. Currently, these gases are mainly supplied by electrolysis or road transportation of compressed or liquefied gas.

Passenger/goods transport

In transport, the competitiveness of hydrogen as a fuel depends on the cost of fuel cells and refuelling stations. Hydrogen fuel cell forklifts have been in operation for years and significant progress has been made with hydrogen fuel cell vehicles, trucks, trains and buses. Some countries successfully operate fleets of hydrogen powered buses for public transport. Unlike more common battery-powered electric vehicles, fuel cell vehicles don't need to be plugged in, and current models easily exceed 450 km on a full tank. They're filled up with a nozzle almost as quickly as traditional petrol and diesel vehicles. While Honda, Hyundai and Toyota remain committed to hydrogen fuel cell vehicles, Elon Musk, CEO of Tesla, dismisses hydrogen fuel cells as "mind-bogglingly stupid" (D'Allegro, 2019).

Minnehan and Pratt (2017) completed a study into the viability of hydrogen as a fuel in maritime applications and concluded that today's zero emission powertrains can meet the propulsion power and energy storage requirements of a wide range of vessels, from small passenger ferries and fishing boats to the largest cargo ships in the world.

Although a couple of small experimental aircraft powered by hydrogen have been built and tested, no definitive plans are in place to move away from fossil fuels for aviation. Hermans (2017) maintains that using liquid hydrogen has some specific advantages for air transport, namely safety, weight, and low hydrogen boil-off because the low outside temperature at cruising altitude reduces the temperature difference with the liquid. He concludes that using liquid hydrogen as a potential energy carrier for air transport deserves serious consideration.

Timing

So, when will we see this transition to a hydrogen-based economy? According to Gigler and Weeda (2018) it has started already, with major milestones expected over the next 25 years, as illustrated in Figure 5. Hydrogen use in industry is well established, but of interest is the forecast establishment of a synthetic fuels industry for shipping and aviation, based on hydrogen and CO_2.

Note the graphic at the bottom of Figure 5: natural gas reforming will gradually give way for electrolysis as the preferred method for hydrogen production from about 2035. Carbon capture and storage (CCS) will be required for hydrogen produced by reforming in the interim.

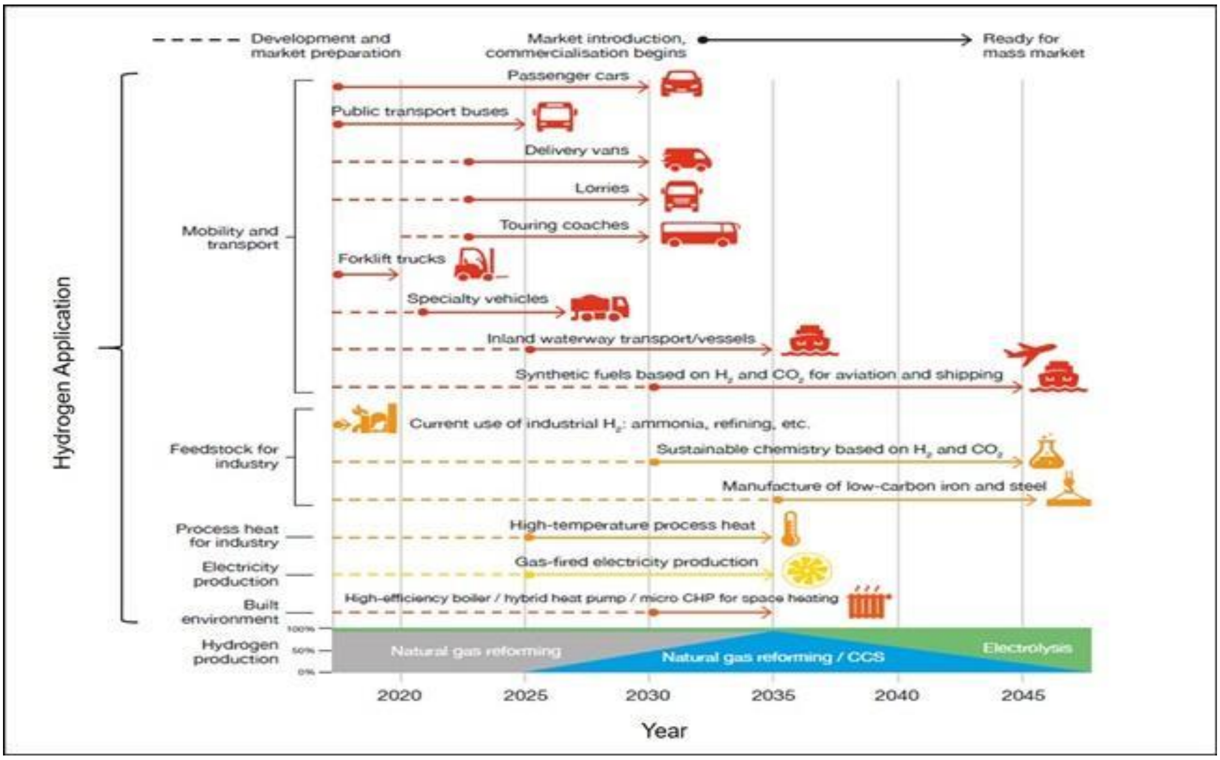

Figure 5: Schedule of implementation for a range of hydrogen applications (Gigler & Weeda, 2018)

Concluding remarks

Hydrogen is important for being able to achieve the social challenge of drastically reducing CO_2 emissions. Although hydrogen is widely used in some industrial applications, it has not yet realised its potential to support clean energy objectives. Moving to a hydrogen economy will take time and will only make sense if hydrogen can be produced economically from renewable sources, or from hydrocarbons with low emissions profiles, i.e. when coupled with carbon capture and storage (CCS).

A major challenge is to reduce the costs for the production and application of hydrogen. This can be done by upscaling (creating critical mass) and by innovating. Focused research and near-term action is required to overcome remaining technological barriers and reduce costs. We need to spread the word about a clean hydrogen economy and (hopefully) more scientists, engineers and politicians will become motivated to participate.

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