

Original Research Article

Prevalence of COVID - 19 Pandemic: A Paradigm Shift to Hydrogen Economy

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Abstract

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Covid-19 pandemic lockdown has slow down the world economic system. The pandemic has cleared the roads, close factories and grounded planes causing severe economic challenges. The damaging impact of the pandemic amid lockdown has been a blessing in guise for the environment because of significant drop in pollution level as transport and industrial sectors shutdown. Transport and industrial sectors are major contributors to environmental degradation through various emissions as a result of fossil fuel consumption. Energy consumed by transport and industrial sectors will have to shift to viable, readily available, economically and environmentally friendly with no carbon build up post Covid-19 pandemic. Hydrogen energy remains the best alternative option technologies containing green house gas emission and pollutions of several forms. Hydrogen holds the potential to provide a clean, reliable, renewable and economical source of energy for meeting the growing and unending global energy needs post pandemic. The present paper explores the economic feasibility and potential of hydrogen to serve as a competitive fuel option post pandemic. In this paper, the role of hydrogen as an energy carrier hydrogen economy structure, potential of hydrogen economy, hydrogen production methods, hydrogen application and the economic and environmental importance of hydrogen as a viable fuel option post covid-19 pandemic were discussed. There will be a surge in demand and investment for hydrogen economy post Covid-19.

Keywords: Corona virus, environmental degradation, hydrogen economy, clean energy, renewable sources, non renewable sources, economic impact, environmental impact

INTRODUCTION

Since December 2019, there has been outbreak of novel corona virus named covid-19 reported to have emerged from Wuhan in china. The disease continued to spread from China to many other part of the world, affecting 196 countries by March 25, 2020 (Chen et al., 2020; Xu et al., 2020). This spread aroused the attention everyone worldwide. This transmission of the virus is from person to person through contacts influenced by environmental factor such as climatic conditions, population's concentration and medical quality (Wang et al., 2020). In order to curtailed and controlled the spread of Covid-19, many cities in the world lockdown completely. Majority of roads, factories/industries and airport have been

grounded in ordered to significantly reduce person to person contact and transmission. The consequent of the decision to lockdown resulted in dramatic improvement in the pollution level of air, water and soil quality. The global weather condition becomes better and the skies become blue and clearer. Covid-19 seems to be a blessing in disguise for the environment and implying that transport and industrial sectors are major contributors to global pollutions. Transport and industrial sectors have direct impact on global energy consumption. Restriction of both sectors have brought down current oil demand and consequently lowered green house gases. NASA satellite image have shown that pollutions level reduce remarkably

in Chinese cities, Western Europe, United States and Iran over the lockdown (Bauwens et al., 2020) and suggesting that there must be a paradigm shift in world energy demand for a cleaner and greener energy after the lockdown when transport and industrial sectors will be opened. Therefore a shift toward hydrogen economy is inevitable. Hydrogen energy have the potential to redefine global energy landscape, providing options beyond oil and coal which have caused environmental degradation, issues on climate change and concerned for human health. Hydrogen economy will bring about a balance in economic goal, lower pollution level which can help the most vulnerable fight against future pandemic. Hydrogen energy is the best alternative energy to oil, coal and nuclear energy.

Hydrogen as energy carrier

Hydrogen is an abundant element on earth but not naturally occurring. Its combine with other element to form many common materials. It exists in water, hydrocarbon, coal, petroleum, natural gas, oil shale, biological material, carbohydrate, cellulose and protein. Hydrogen is not a primary energy source but alternative replacement to fossil fuel. With hydrogen energy technology, zero carbon foot print can be achieved from transport and industrial operations. As fascinating energy carrier, it can be produce from electricity and water. When combusted with oxygen, its form water and the water is return to nature. Little or no pollutants are generated or emitted. Currently, hydrogen is majorly produced as chemical feedstock. According to USDOE (2002) nine million ton of hydrogen are consumed annually in chemical production, petroleum refinery, metal treating and electrical applications in United States.

Hydrogen economy structure

Hydrogen economy is the system of production, distribution, consumption and utilization of hydrogen gas energy. It is composed of five segments: hydrogen production, storage, delivery, conversion and end-user applications. Fossil fuel, electricity and nuclear energy can be utilized to generate hydrogen through chemical, electrolytic, thermal and photolytic process. Hydrogen can be stored as liquid or gas and be delivering to pipelines, trucks, trains, airplane and barges. With hydrogen gas as alternative energy air, water and soil quality will improve without any pollution as experienced during covid-19 lockdown.

Potentials of hydrogen economy

Currently energy sources are dominated by fossils fuels

(coal, oil and gas) are considered as largest source anthropogenic emissions of green house gas particularly carbon dioxide into the atmosphere that is largely responsible for global warming and climate change (Zanganeh and Shafeen, 2007). Increasing fossil fuel consumption has brought serious problems to the world including intractable energy security (Shaikh et al., 2016), green house emission (Lin and Xu, 2018) and air pollution (Tilt, 2019). The impact of covid-19 around the world couple with global oil energy crisis, pollution and scarcity require the need to diversify and explore energy resources toward an alternative energy fuel. The alternative fuel must be clean, technically feasible, economically competitive, environmental friendly, readily available (Meher et al., 2006) with no negative issues on human health and public welfare. Numerous potential alternative fuels have been proposed which include biodiesel, methanol, ethanol, hydrogen, boron, natural gas, liquefied petroleum gas (LPG), Fischer-Tropsch fuel, p-series, electricity and solar fuel (Mustafa Balat, 2008). Among all of these alternative fuels, hydrogen has the highest specific energy content of all conventional fuels (Campen et al., 2008) and is the most abundant element in the universe. Hydrogen economy is global solution to energy crisis/scarcity, air pollution health effects and global warming. Moreover hydrogen can be generated or regenerated from variety of energy sources like coal, nuclear, wind, solar energy. Hydrogen thus offers the promise energy security and availability through great production and use of domestic energy resources. Eventually the world will run out fossil fuels and at that time the society will be force to transition of alternative fuel of hydrogen. Most importantly application of hydrogen energy in transport sector through fuel cell vehicles and industrial sector will improve urban and industrial air quality thereby reduces generation of photochemical smog in urban / industrial environment. Since transport and industrial sectors are major contributor to climate change which result to global warming but with wide application of onboard hydrogen fuel cell technology on transport and industrial sectors, zero emission will be achieve thereby hydrogen is a solution to global warming. Global market for hydrogen is already greater than \$40 billion per year (Tilt, 2019). This include hydrogen used in ammonia production (49%), petroleum refining (37%), methanol production (8%), and miscellaneous smaller-volume uses (6%) (10). Present utilization of hydrogen is slightly above 3% of the energy consumption and with a growth rate estimated at 5–10% per year (Prince-Richard et al., 2005) It can be foresee and predicted that hydrogen energy demand production and consumption will increase after covid-19 pandemic. Australia and Germany governments have made tremendous investment in hydrogen supply pre covid-19 pandemic (AREA, 2019) and more investment will be done by first world countries post covid-19 pandemic.

Table 1. Properties of hydrogen compare to natural gas and gasoline

| Properties | Hydrogen | Natural Gas | Gasoline |
|---|-----------|-------------|--------------------|
| Molecular weight (g/mol) | 2.016 | 16.04 | 110 |
| Mass density (kg/N _A m ³) at P=1, T=0°C | 0.09 | 0.72 | 720-780 |
| Mass density of liquid H ₂ at 20 K (kg/N _A m ³) | 70.9 | - | - |
| Boiling point (K) | 20.2 | 111.6 | 310-478 |
| Higher heating value (MJ/kg) (assumes water is produced) | 142.0 | 55.5 | 47.3 |
| Lower heating value (MJ/kg) (assumes steam is produced) | 120.0 | 50.0 | 44.0 |
| Flammability limits (% volume) | 4.0-75.0 | 5.3-15.0 | 1.0-7.6 |
| Detonability limits (% volume) | 18.3-59.0 | 6.3-13.5 | 1.1-3.3 |
| Diffusion velocity in air (m/s) | 2.0 | 0.51 | 0.17 |
| Ignition energy (mJ) | | | |
| At stoichiometric mixture | 0.02 | 0.29 | 0.24 |
| At lower flammability limit | 10 | 20 | not available |
| Flame velocity in air (cm/s) | 265-325 | 37-45 | 37-43 |
| Toxicity | Nontoxic | Nontoxic | Toxic above 50 ppm |

Properties of hydrogen as industrial and transport fuel.

Hydrogen is a colourless, odourless, tasteless gas and nontoxic gas found in the air at concentration of about 100 ppm (0.01%) (Suban et al., 2001). It is the lightest known substance: it is 14.4 times less dense than air. It is the most abundant element in the universe although in combine form, making up to 75% of normal matter by mass and over 90% by number of atoms (Mariolakos et al., 2007) to provide energy, hydrogen can be either burned or reacted chemically at very high conversion efficiency and will produce virtually little/no emissions. Like any other fuel source, hydrogen has both strengths and weaknesses based on its chemical and physical properties. Below are the properties of hydrogen compare to natural gas and gasoline as industrial and transport fuel: Table 1

As an industrial and transport fuel option while considering environmental concerns, hydrogen exhibits numerous advantageous properties including its high diffusion velocity, highest heating value of any fuel (per kilogram), wide range of flammability and detonability limits, low ignition energy, high flame speed, and nontoxicity. Because hydrogen diffuses very rapidly, it will disperse quickly from a leak, and doesn't form puddles that can explode.

Table 1 show that the heating value of fuels, or the amount of heat that is transferred from the complete combustion of fuels in air increases with the hydrogen to carbon ratio (H/C). Thus, gasoline has the lowest heating value and hydrogen the highest, and therefore a very high potential to do useful work in an engine. The broad range of flammability and detonability limits of hydrogen

(the concentration of the fuel in air that can ignite or explode respectively) means that hydrogen does not have to be in stoichiometric ratios to be combusted; it can be burned in leaner concentrations leading to reduce fuel consumption. In other words Hydrogen engines can be operated more effectively on excessively lean mixtures than gasoline engines. As little as 4% hydrogen by volume with air produces a combustible mixture (Norbeck et al., 1997) and Hydrogen can detonate over a very wide range of concentrations when confined, however, unlike many other fuels; it is very difficult to detonate if unconfined.

Additionally, the energy required to ignite a mixture of hydrogen in air is low at stoichiometric mixture and lower flammability limit, 0.02 and 10 MJ respectively. The flame speed of hydrogen is high, both factors which aid in the complete mixing and combustion of the fuel in a hydrogen combustion engine. The nontoxicity of hydrogen is also an added bonus when compared to gasoline or any other fuel. When looked at with its environmental friendliness, except for very small levels of NO_x, hydrogen produces only water when burned or chemically reacted. Its physical properties make it an intriguing fuel option. However, hydrogen also has several drawbacks. Compared to natural gas and gasoline, hydrogen is a very low-density diatomic gas, and thus must be compressed to very high pressures, liquefied at a temperature of about -252°C, or stored in some other specialized fashion in order to condense a reasonable amount in a reasonable volume. As a compressed gas, hydrogen exhibits rather low energy density, containing about one-third the energy as an equivalent volume of natural gas at the same pressure and as a cryogenic liquid, about one-third the energy as an equivalent

volume of gasoline. Hydrogen is also an extremely small molecule, diffusing more readily than other fuels, and is more likely to leak. Moreover, it can even diffuse into some metals and cause embrittlement therefore hydrogen systems thus necessitate special materials considerations. The lower flammability limit of hydrogen, above considered as a strength, also means that if hydrogen leaks and builds up in low concentrations in an enclosed space, accidental explosion can occur or if fuel and air mix outside the cylinder of an engine, backfiring can occur. Due to a high flame velocity, this explosion could also travel very rapidly. A potential solution to backfiring is direct injection of hydrogen gas into the cylinder prior to spark generation which also increases engine efficiency by allowing the engine to run at higher compression ratios than if it ran on gasoline. Nonetheless, backfiring remains a potential risk of a hydrogen combustion engine. Hydrogen clearly exhibits several attractive physical properties when it comes to fuel applications, but it is also important to remember its potential risks when implementing it in industries and transport sector.

Laboratory tests conducted on internal combustion engines burning hydrogen demonstrate good performance (Berry et al., 1996). In comparison with an engine burning gasoline, the emission of nitrogen oxides is far less for the engine-fueled hydrogen. The product of hydrogen combustion with air is water vapor and negligible pollution when the peak temperature is limited. Some oxides of nitrogen (NO_x) are formed at very high combustion temperatures (< 2300 K); fortunately, the auto ignition temperature of hydrogen is only 858 K (Plass Jr., et al., 1990). The oxide of nitrogen (NO_x) is formed as a result of combustion of air with hydrogen mixture. The air is mixture of gases majorly 78% nitrogen and 21% of oxygen with very small amount of CO₂, noble gases and water vapour. Hydrogen has good properties as a fuel for internal combustion engines in automobiles. Some of the characteristic properties of a hydrogen–air mixture that can definitely influence the engine design and performance are low ignition energy, low ignition energy, low density, wide range of ignition limits, high diffusion speed, and high flame speed (Plass Jr., et al., 1990).

Sources of hydrogen

Hydrogen can be source from variety of primary energy such as fossil fuels, nuclear (Utgikar and Thiesen, 2006), solar (Charvin et al., 2008), wind (Granovskii et al., 2007), hydropower (Tarnay, 1985) and geothermal energy (Sigurvinsson et al., 2006). Different energy resources with various pathways can be utilized to generate hydrogen. Various processes such as methane steaming steam reforming, water electrolysis, high temperature electrolysis, and thermochemical cycles are available to produce hydrogen as well. The main sources for

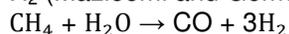
commercial production of hydrogen include natural gas (48%), oil (30%) coal (18%) and electrolysis (4%) of world hydrogen production (Press et al., 2008). Fossil fuels conversions are dominant source of commercial /industrial hydrogen such as natural gas reforming (Häussing et al., 2011).

With respect to production capacities, hydrogen production can also be categorized into 'distributed' or 'centralized' production. Distributed production facilities are smaller in scale and closer to the consumers. As such distributed generations can meet the demand from transportation sector of hydrogen powered fuel cell vehicles during the transition period to a hydrogen economy and once the market expands, the hydrogen production will be scaled up and 'centralized' to take advantage of economies of scale as well as the higher efficiency from larger scale production and to meet the greater amount of hydrogen demand in industrial sector.

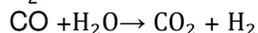
Hydrogen Production Processes/Methods

Steam reforming of Natural Gas

Steam methane reforming (SMR) is a process in which the natural gas or other methane streams, such as biogas or landfill gas, reacts with steam in the presence of a catalyst (usually nickel) to produce hydrogen and carbon monoxide. It is worth mentioning that, natural gas reforming produces for more than 90 % of hydrogen production worldwide and remains the most commonly used method for hydrogen production. This process consists of heating the gas to between 700-1100 °C in the presence of steam and a nickel catalyst. The resulting endothermic reaction breaks up the methane molecules and forms carbon monoxide CO and hydrogen H₂ (Mazloomi and Gomes, 2012).



The carbon monoxide gas can then be passed with steam over iron oxide or other oxides and undergo a water gas shift reaction to obtain further quantities of H₂.



The downside to this process is that its major by-products are CO, CO₂ and other greenhouse gases. Depending on the quality of the feedstock (natural gas, rich gases, naphtha, and others), one ton of hydrogen produced will also produce 9 to 12 tons of CO₂.

According to the Director of Energy of USA (2010), SMR is approximately 72% efficient in hydrogen generation when starting with natural gas. Conversely, on a lower heating value basis, SMR produces a hydrogen-rich gas that is typically on the order of 70–75% hydrogen on a dry mass basis, along with smaller amounts of methane (2–6%), carbon monoxide (7–10%), and carbon dioxide (6–14%) (Sharma and Ghoshal, 2015).

In addition, SMR is not an attractive production route

for a developed hydrogen economy. This is due to the fact that the order-of-magnitude increase in demand would deplete our finite reserves. Moreover, the concentration of gas reserves in relatively few regions of the world could lead to geopolitical tension and unstable supplies. Environmental impact is also a major concern because reforming natural gas to hydrogen produces as much pollution and CO_2 as burning the natural gas directly. Generation of hydrogen from natural gas is a well-established process. If sufficient quantities are produced to power the world's cars and light trucks it would strain the world's supply of conventional methane, making natural gas as geopolitically sensitive as an oil (Sharma and Ghoshal, 2015).

Gasification of coal and other hydrocarbons

Currently, gasification processes are mainly used in large-scale integrated gasification combined cycle power plants (due to the low flexibility of synthesis gas production) in order to supply base energy load. But in a short-term future, the possibility to produce hydrogen from syngas could make gasification technologies very interesting also for medium and small-scale industrial applications. To this aim, Sotacarbo, Ansaldo Ricerche, ENEA and the Department of Mechanical Engineering of the University of Cagliari developed an integrated gasification and syngas treatment process for combined production of hydrogen and electrical energy for medium and small-scale commercial applications (Deiana et al., 2007).

The partial oxidation process termed as "gasification", generates hydrogen from a wide range of hydrocarbon fuels, including coal, heavy residual oils, and low-value refinery products. In this process, the hydrocarbon fuel is made to react with oxygen in a less than the stoichiometric ratio, yielding a mixture of carbon monoxide and hydrogen at 1200 to 13500C (Sharma and Ghoshal, 2015). Coal is a practical option for making hydrogen in large plants. Worldwide coal reserves and commercially available technologies make coal a practical option for producing hydrogen in large plants. Compared to the existing methods (i.e. electrolysis), gasification is more suitable for converting coal to hydrogen (Acar and Dincer, 2014).

The process begins with partial oxidation, which means some air is added to the coal, which generates carbon dioxide gas through traditional combustion. Not enough is added, though, to completely burn the coal (only enough to make some heat for the gasification reaction). The partial oxidation also makes its own gasification agent, carbon dioxide. Carbon dioxide reacts with the rest of the carbon in the coal to form carbon monoxide (this is the endothermic gasification reaction, which needs heat input). No hydrogen yet.

Carbon monoxide in the gas stream is now further reacted with steam, generating hydrogen and carbon dioxide. Now we are making some hydrogen. The hydrogen can then be run through an on-site fuel cell to generate high-efficiency electricity. Brown coals are generally preferred for gasification over black coals for several reasons. The main reason is that, because of the high oxygen content of this type of coal, it is less chemically stable and therefore easier to break apart during the gasification reaction. Also, there is a small boost from the hydrogen that is already present in the coal (Allen, 2018).

Hydrogen produced from this method is not a zero-emission fuel. Carbon dioxide is generated through the combustion and thermal decomposition reactions and is also a by-product of the reaction between carbon monoxide and water to make hydrogen and carbon dioxide. Figure 1

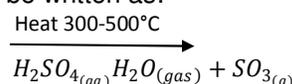
Hydrogen Production from Nuclear Energy

Thermochemical water splitting

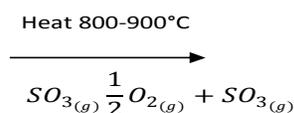
Thermochemical water splitting uses high temperatures from nuclear power plant reactions to produce hydrogen and oxygen from water. Thermochemical water splitting processes use high-temperature heat (500°C or more) to initiate a series of chemical reactions that generate hydrogen. The chemicals used in the process are reused within each cycle, creating a closed-loop that uses up only water and produces hydrogen and oxygen.

Thermochemical water splitting cycles have a major advantage of not requiring catalysis to drive individual chemical reactions. Except for water, which is the material source of hydrogen production, all chemicals used in the thermochemical cycle can be recycled. Other advantages of thermochemical water splitting cycles are little or no need for $\text{O}_2 - \text{H}_2$ separation membranes, reasonable temperature requirement range of 300-1000°C and zero or low electrical energy requirement.

Being fully developed and demonstrated in Japan and the US, the S-I cycle (Sulfur-Iodine cycle) is considered as technically viable. Though there are numerous setbacks associated with this method of hydrogen production. The first reaction of S-I a cycle is thermally driven and it can be written as:



The product gases (H_2O and SO_3) are separated heated up to 800-900C. Then SO_3 gas is decomposed thermally according to



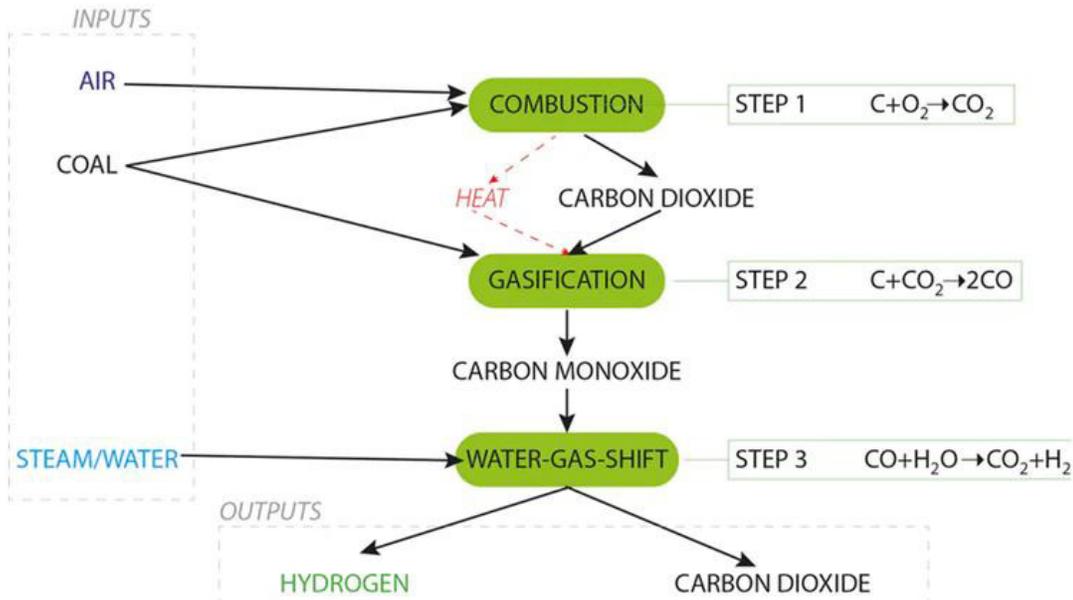
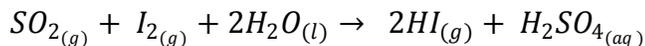
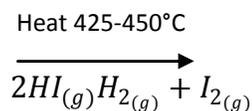


Figure 1. Production of Hydrogen from gasification of coal (Allen, 2018).

After separation from O_2 , SO_2 undergoes an exothermic reaction with iodine and water which occurs at low temperatures spontaneously:



Lastly, HI thermally decomposes into H_2 at temperatures around 420-450°C:



Since there are no side reactions happening during the S-I cycle, it is reasonably straightforward to separate and reuse the chemicals used in Reactions (3)-(6). Because of the relatively high reaction temperature requirements of S-I cycles, there are not many sustainable thermal energy sources available to drive the individual reactions in the cycle. Nuclear, concentrated solar, and biomass combustion heat can be listed as possible sustainable thermal energy sources to drive the S-I cycle reactions. In the hybrid version of S-I cycles, the hydrogen-generating reaction is supported electrochemically (Dincer and Acar, 2014).

Hydrogen Production from Renewable Energy

Biomass gasification

Biomass sources such as wood and agricultural products,

solid wastes, landfill gas and biogas, ethanol, biodiesel and so on can be processed for the production of hydrogen. Biomass conversion technologies are divided into two categories: thermo-chemical and biochemical processes. Thermochemical processes tend to be less expensive because they can be operated at higher temperatures and therefore achieve higher reaction rates. They involve either gasification or pyrolysis (heating biomass in the absence of oxygen) to produce a hydrogen-rich stream of gas known as "syngas" (a blend of hydrogen and carbon monoxide) (Sharma and Ghoshal, 2015). Though biomass gasification has not been able to produce hydrogen on a large scale at a competitive price. Nevertheless, this method could still be used to generate energy from domestic and agricultural waste in a clean way.

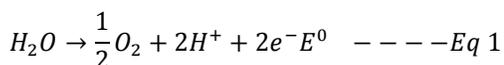
One method of generating hydrogen from biomass begins with processing the organic materials at high temperatures, but without combustion. When combined with oxygen and steam, the reaction results in carbon monoxide, carbon dioxide and hydrogen gas. This gasification process can take the carbon monoxide that is produced and combine it with additional steam to produce additional hydrogen and carbon dioxide, which is recycled through the natural plant respiration cycle and generate additional biomass. Alternative options may involve biological agents, such as anaerobic bacteria or fermentation, or pyrolysis, which uses the same gasification process, but without the presence of oxygen. Research in this field is suggesting new ways to improve efficiency and increase the implementation of hydrogen generation from biomass. Along with analysis that shows that biomass feedstock usable for energy production

should be plentiful, the future usage of hydrogen production techniques related to biomass should continue to grow. Looking toward further opportunities, research being conducted promises to develop bacterial and microbial actors that increase production efficiency, while additional efforts focus on methods to lower both production costs and the costs of obtaining the feedstock.

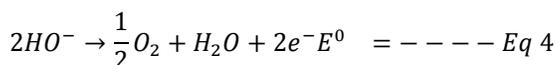
Electrolysis (Water-electrolysis)

Water electrolysis is the process whereby water is split into hydrogen and oxygen through the application of electrical energy, as in Eq. (6). Typically, a water electrolysis unit consists of an anode, a cathode separated with an electrolyte, and a power supply. The electrolyte can be made of an aqueous solution containing ions, a proton exchange membrane (PEM) or an oxygen ion-exchange ceramic membrane. A direct current (DC) is applied from the negative terminal of the DC source to the cathode (seat of the reduction reaction), where the hydrogen is produced. At the anode, the electrons produced by the electrochemical reaction return to the positive terminal of the DC source.

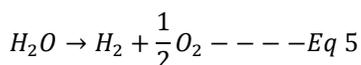
For the case of water electrolysis in an acid aqueous electrolyte, the processes that occur at the anode and the cathode are described, respectively, by Eqs. 1 and 2:



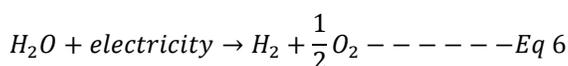
The half-reactions occurring at the cathode and the anode respectively can be written as:



The global reaction for the two cases is:



Electrolysis of water is not a spontaneous phenomenon because the standard global reaction potential is negative. Therefore, it needs an extra intervention (power source) and the global reaction can be written as:



Electrolysis of pure water requires excess energy in the form of overpotential to overcome various activation barriers. Without the excess energy, the electrolysis

of pure water occurs very slowly or not at all. This is in part due to the limited self-ionization of water. Pure water has an electrical conductivity of about one-millionth that of seawater. Many electrolytic cells may also lack the requisite electrocatalysts. The efficiency of electrolysis is increased through the addition of an electrolyte (such as a salt, an acid or a base) and the use of electrocatalysts.

Water electrolysis has some unique qualities. Electrolysis could be used for hydrogen production at any place around the globe. The only requirements of this production are electricity and water where the production rate/capacity could be tuned for a certain demand at any place. With regard to the characteristics of water electrolysis, this method is capable of producing absolutely sustainable and clean hydrogen and also oxygen can be obtained for hospitals and world's water ways remediate hypoxia issues. This goal can be achieved only if the required electricity is obtained from an emission-free method such as wind, solar, geothermal systems, ocean wave or other renewable and green sources (K. Mazloomi, 2012).

Hydrogen Storage

Hydrogen gas has a good energy density by weight, but poor energy density by volume against hydrocarbons; hence it requires a large storage facility. Storage of Hydrogen gas is one of the key regions where huge advancements are required to hasten the utilization of hydrogen in transportation, refining, power generation applications and in chemical industries. There are several ways of storing hydrogen, but the widely recognized methods are: High-pressure storage in the gaseous form, very low-temperature storage in the liquid form and hydride-based storage in the solid form

Hydrogen stored as compressed gas in high-pressure tanks

The easiest way to decrease the volume of a gas, at constant temperatures, is to increase its pressure (Boyle's law). Storage of hydrogen gas typically requires high-pressure tanks (200 to 350 bar cylindrical tank pressure), although systems with at least 700 bar capacity are currently under development. These cylinders/tanks are being made from (i) steel (ii) Aluminum core encased with fiberglass and (iii) Plastic core encased with fiberglass. Compressed hydrogen storage systems have been demonstrated in hundreds of prototype fuel cell vehicles and are available commercially at low production volumes. While compressed hydrogen typically is stored at near-ambient temperatures, "cold" (sub-ambient but greater than 150 K) and "cryogenic" (150 K and below) compressed hydrogen storage are being investigated due to the

higher hydrogen densities that can be achieved at reduced temperatures

Hydrogen Stored as Liquid in tanks

Another industrial technique for storing maximum hydrogen in a restricted volume is to convert hydrogen gas to liquid hydrogen by cooling it to a very low temperature.

Hydrogen turns into a liquid when it is cooled to a temperature below -252.87°C . At -252.87°C and 1.013 bars, liquid hydrogen has a density of close to 71 kg/m^3 . At this pressure, 5 kg of hydrogen can be stored in a 75-litre tank. In order to maintain liquid hydrogen at this temperature, tanks must be perfectly isolated. Currently, storing hydrogen in the liquid form is being reserved for certain special applications, in high-tech areas such as space travel

Hydrogen stored as solid

The storage of hydrogen in solid form that is stored in another material is also a promising avenue of research. Methods for storing hydrogen in solid form are techniques involving absorption or adsorption mechanisms of hydrogen by a material. One example is to form solid metallic hydrides through the reaction of hydrogen with certain metal alloys. This absorption is the result of the reversible chemical combination of hydrogen with the atoms that comprise these materials. The most promising materials are composed of magnesium and alanates. Only a low mass of hydrogen can be stored in these materials, which is currently the major downside of this technology. In fact, the best materials currently generate a ratio of hydrogen weight to the total weight of the tank of not more than 2 to 3%. Before considering large-scale applications, it is also important to master certain key parameters such as kinetics (cell performance), the temperature and pressure of the charge and discharge cycles of hydrogen in these materials.

Hydrogen Application

Vozniuk et al., 2019 revealed that hydrogen is one of the key starting materials used in the chemical industry with an annual worldwide production of about 50 million tons, currently, the largest amount ($\approx 95\%$) of the total manufactured hydrogen is consumed mainly by two industrial segments: the chemical sector, accounting for 65% of the market share (ammonia and methanol synthesis $\approx 63\%$; liquid hydrocarbons and higher alcohols synthesis $\approx 2\%$) and the refining sector, which accounts for 30% of the market share (hydrotreating and

hydrocracking processes for obtaining high-grade petrochemical products). The other present uses, with $\approx 5\%$ of the total consumption, include the food industry (sorbitol and fat processing), the metallurgical industry (direct reduction of iron ore), the semiconductor industry and so on. Post covid-19 lockdown, there will be more demand and investment for hydrogen economy most especially in transport and industrial sectors as a fuel source. Covid-19 pandemic has automatically reset world energy consumption toward hydrogen economy. Global environment will sustain natural balance of earth for healthy and clean atmosphere as experienced during the covid-19 lock down with hydrogen economy.

The economic and environment importance of hydrogen as a viable fuel option post Covid-19 pandemic

Australia, Germany, Norway, Denmark, United States, Canada, South Korea and Japan have made massive investment toward hydrogen economy, more seriously energy and environmental concern countries are also actively developing and investing their own (Abe et al., 2019) because the future of world energy consumption is toward hydrogen economy. In order for hydrogen to be considered an economically viable fuel option it must be produced and delivered at a stable price that is competitive with the current price of refined petroleum (gasoline /diesel). Furthermore, the cost of hydrogen economy infrastructure development must be considered, the availability and accessibility of hydrogen must be realized through production and distribution capacity. Some existing pipelines could even be modified to support hydrogen economy for distribution. However long-distance distribution network may not be required as hydrogen can be produced regionally where it is needed. One major benefit of hydrogen is that it can be produced from a variety of primary sources and different production processes as earlier discussed; therefore accessibility of hydrogen could be almost anywhere in the world. Another benefit of hydrogen over other fuel options is that after combustion/reaction product is water vapour there is no carbon footprint or greenhouse gases. The world will be in its natural state as experienced during covid-19 lockdown. Using hydrogen as a feasible fuel option will not change our transport system as hydrogen can be used as fuel directly in internal combustion engines not much different from engines used with gasoline (Balat, 2005).

As a viable fuel option for industrial and transport sectors, hydrogen has peculiar properties which include rapid burning speed which enhances performance of engines, high octane number with non-toxicity and ozone-forming potential. A hydrogen engine is easy to start in extreme cold weather conditions because it remains in gaseous state until it reaches a low temperature such as 20K (Ma

et al., 2003). Although engine combustion products of hydrogen are clean; consisting of water and little amount of nitrogen oxides (NO_x), since there is little or no presence of volatile organic compounds a steady state of natural balance will always be achieved where relative low ozone exist naturally in the troposphere of the Earth. Production hydrogen from electrolysis from splitting of water can result to elevated oxygen level which may enhance good breathing for land and aquatic life. With hydrogen as fuel option the earth will always be its fresh natural state and human health will not threaten. Life span of people where hydrogen economy is entrenched is likely to increase. The planet can become hopeful of climate neutrality in the years ahead with hydrogen economy. A hydrogen economy has long terms goal of many nations, can potentially confer and be a solution to energy security, along with financial, environmental and health benefits to the world.

CONCLUSION

No doubt Post covid-19 pandemic will be a time for global energy shift toward hydrogen economy. Hydrogen economy will make the world better place for improved public health living, the environment will be devoid anthropogenic pollutions from fossil fuel and there will be sustainable earth balance. Hydrogen economy comes with increase in oxygen level in atmosphere. Life span of living matter may likely to improve. Hydrogen economy will lead to decarbonization of the atmosphere as there are no carbon footprint in the hydrogen engine emissions. With hydrogen economy there is no political power tussle and economic unrest as hydrogen fuel could be produce anywhere in the world. Hydrogen economy has the potential of more jobs creation and other economic benefits. It can result to stable, inexhaustible energy supply .Electricity becomes cheap and energy is readily accessible. The world will be a better place and relatively at peace. Hydrogen economy is the only energy resources that can meet world energy needs, its emission goal and find appropriate solution for region of the world. Hydrogen economy is a more reliable and resilient energy system.

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