A Comprehensive Review on Hydrogen Fuels Technology

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Abstract – Global warming due to Green House Gas emissions has become a major issue of concern. While this was ignored over the last many years, its impact is now more visible leading to unusual weather phenomena across the globe. It is hence imperative to urgently look at various sources of emission and take immediate measures which support in limiting it. At the same time, the economics is also extremely important in order that industry is able to commercialize without significant cost impact. Keeping the above in mind, technological research and advancement in close collaboration with industry is required. The transportation sector being one of the major sources of emission has been in focus. A lot of work has been done on various technologies which could potentially replace the use of fossil fuels. Electric vehicles based on Lithium-ion batteries have seen relatively good success, however there are drawbacks like heavy batteries leading to lower mileage. This brings us to the other promising technology which is Hydrogen fuels. While there are a number of routes by which hydrogen can be manufactured, the cleanest route is by electrolysis using renewable sources of energy. The cost of this technology is currently prohibitively high, and work is being done on the same. It is currently a chicken and egg kind of situation - Faster technology adoption will need better cost position at the same time efficiencies of scale will need to be achieved.

1. INTRODUCTION

Global Warming has led to a constant increase in the annual temperature of the Earth. This increase was first recorded in the year 1880 and has since been recorded every year. Between 1880 and 1980, this increase was recorded at an average of 0.07 degree Celsius every ten years. However, since 1981 to the current time, this rate of change in the temperature of the earth has increased drastically. Since 1981, the increase in the annual global temperature of the earth has been recorded at an astounding 0.18 degree Celsius every 10 years. In the current situation, limiting this increase in temperature to its lowest level has become a problem of utmost importance. [1]

A major factor that contributed to this increase in the temperature has been the Industrial Revolution. The industrial revolution took place in the late 18th century in the United States of America and Europe. The industrial revolution can simply be put as a shift from an economy based on agriculture and handmade crafts to an economy that is based on industry and manufacturing of machines. This led to the introduction of machines which would later lead to the system of mass manufacturing. These machines were run on energy produced by fossil fuels which would lead to the formation of GHG (Greenhouse gases). As industrialization began to spread throughout civilization, the formation of these GHG emissions also increased. This played a crucial role in the increasing temperature of the Earth. [2]

In the current scenario, a major contributors to Global Warming is the transportation sector. The internal combustion engines used in the transportation sector led to the emission of a variety of greenhouse gases such as carbon dioxide (CO_2), Methane (CH_4), and Nitrous oxide (NO_2) from the tailpipes. Hydrofluorocarbons are also emitted from the air conditioners. The highest contributor to the Greenhouse gases is carbon dioxide as it is the gas emitted in the highest amount from the vehicles. To reduce these emissions, various alternatives have been researched such as Hybrid-Electric Vehicles (HEV's), Electric Vehicles (EV's) and Hydrogen Fuel Cell Vehicles. Hybrid-Electric Vehicles run on a combination of electric motors and an IC Engine. Electric Vehicles on the other hand rely purely on electric motors. [3][4]

The purpose of this paper is to showcase the potential of hydrogen fuel as the best alternative to current fossil fuels and list the advantages and disadvantages of the same.

2. HYDROGEN

Hydrogen is the first element in the periodic table. It is the most abundant substance present in the universe. It is found in water (H_2O), hydrocarbon substances as well as in other types of organic matter. [6][7] The atomic number of Hydrogen is 1 and its atomic mass is 1.008. It is the lightest and simplest element in the universe, and it consists of a single proton and an electron. Under the standard conditions, hydrogen exists as a gas, and it is colorless, odorless, and tasteless. It is also highly combustible. Hydrogen is an energy carrier, i.e., it can be used to transport energy produced from one source to the other.[8]

2.1 Hydrogen Fuels

Hydrogen fuel is a zero-carbon emission fuel.

Hydrogen gas (H_2) on reaction with pure oxygen (O_2) leads to the formation of water and also the release of energy. The chemical reaction is shown below-

$2H_2$ (g) + O_2 (g) → $2H_2O$ (g) + energy

This is an exothermic reaction, meaning that energy is released on the completion of the reaction. This energy can be used to power applications where energy is required. One of the major applications is the use of hydrogen fuel for transportation by producing vehicles that work on the principle of burning of hydrogen fuels instead of the current Internal combustion engines that use fossil fuels to power the vehicles and thus lead to the emission of greenhouse gases which degrade the environment.

If the reaction is carried out in atmospheric air instead of being carried out in pure oxygen, then along with the formation of water vapor and the release of energy, it would also lead to the formation of small amounts of nitrogen oxides.

3. METHODS OF PRODUCTION

A multitude of methods is available for the production of hydrogen. It can be produced from widely available resources such as natural gas, coal, biomass, and waste. Furthermore, renewable resources such as solar and wind energy can also be utilized to produce hydrogen. The use of resources such as natural gas and coal for the production of hydrogen would lead to the production of Carbon dioxide (CO_2) which would not help achieve the goal of reducing carbon emissions to the highest extent possible. If renewable sources of energy were to be used, an energy production system with virtually no emission/production of air pollutants and Greenhouse gases would be achievable.[9]

In our current scenario, as hydrogen does not occur naturally in large amounts on the earth, but rather in the form of water, hydrocarbons and other organic compounds, hydrogen has to be extracted from one of these sources. Therefore, to be able to produce hydrogen on a large scale, input energy is required.

Majority of the hydrogen is made from natural gas. This is done by steam reforming of natural gas, partial oxidation of methane and gasification of biomass, coal, and wastes. These methods lead to the formation of GHG which cause harm to the environment and lead to global warming.

3.1 Steam Methane Reforming (SMR)

Steam reforming consists of several steps, which are, steam reforming, water gas shift, and purification of hydrogen. In the first step of steam reforming, natural gas, which is mainly comprised of methane, enters a steam reformer along with steam. The reaction that takes place is-

$CH_4 + H_2O \leftrightarrow CO + 3H_2$

This reaction is an endothermic reaction, i.e., it is a reaction that requires the input of energy for it to proceed. This external energy is provided in the form of heat and is generally provided by the combustion of a small amount of the natural gas, or the burning of waste gases formed in the process. This leads to the formation of waste gases known as flue gas formed by the combustion of natural gas required to run the SMR equipment. The reaction is carried out at temperatures ranging from 700^{0}C to 1100^{0}C. This reaction leads to the breakdown of methane (CH_4) into Carbon Monoxide (CO) and Hydrogen (H_2) gas. The Carbon Monoxide formed is known as a synthetic gas or syngas.

After the process of reforming, the syngas, i.e., Carbon Monoxide (CO) is fed into one or more shift reactors. These shift reactors work to increase the concentration of hydrogen produced by using the water-gas shift reaction. The reaction is as follows-

$CO + H_2O \rightarrow CO_2 + H_2$

The water-gas shift reaction is an exothermic reaction, i.e., it releases energy in the form of heat. It is carried out at temperatures

As can be observed, this reaction leads to the formation of Hydrogen gas (H_2) and thus the amount of hydrogen produced is increased by the conversion of Carbon Monoxide to Carbon Dioxide. Thus, the gas obtained from the shift reactor mainly consists of Hydrogen (H_2) along with Carbon Dioxide (CO_2), Methane (CH_4) and small quantities of Steam (H_2O) and Carbon Monoxide (CO).

The final step in the Steam reforming process is the purification of the hydrogen obtained from the process. As stated above, the gas obtained from the shift reactor is not pure hydrogen but is a mixture of gases. These gases must therefore be purified in order to separate the hydrogen gas from the waste gases. The degree to which the hydrogen needs to be purified depends upon the application for which the hydrogen gas is being produced. [9][10][11]

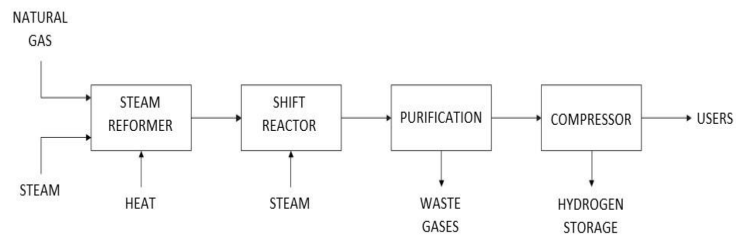

Fig -1: Steam Reforming of Hydrogen

3.2 Gasification of coal, wastes or biomass

The process of gasification of coal, wastes or biomass such as agricultural residues, energy crops or municipal solid waste is similar to the process of steam reforming. Both processes involve the production of syngas which is then passed through shift reactors and purification techniques to obtain the hydrogen at the desired level of purity. The difference between the processes is the addition of the gasification step at the beginning of the process.

Gasification is the step where coal, wastes or biomass are gasified in high pressure/temperature vessels to produce gases such as Nitrogen (N_2), Carbon Monoxide (CO), Hydrogen (H_2) and, Carbon Dioxide (CO_2) in order of highest fractions obtained. This process is carried out by heating the feedstock to very high temperatures so as to produce gases. These gases can then undergo further reactions to form syngas (Steam Reforming stage). The rest of the process is similar to the Steam Reforming Process where the syngas obtained from the gasification and the following steam reforming stage is then passed through shift reactors and purifiers to increase the concentration and purity of the hydrogen produced. [9][12][13][14]

3.3 Partial Oxidation of Hydrocarbons

Partial oxidation of hydrocarbons, as the name suggests, produces hydrogen by the partial oxidation of natural gas or hydrocarbons such as coal and residual oil. The partial oxidation reaction is given as follows-

$$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$$

As can be seen in the above reaction, the feedstock (methane) is being oxidized and this results in the formation of carbon monoxide (CO) and hydrogen gas. This is an exothermic reaction and hence releases energy in the form of heat. This reaction can be carried out without catalysts; however, the addition of catalysts greatly improves the yield of hydrogen produced from the reaction.

The partial oxidation reaction takes place in reactors known as partial oxidation reactors. Syngas is obtained from the partial oxidation reactor which is then fed into shift reactors and further into purifiers to improve the concentration and purity of the hydrogen gas to be obtained. [9][10]

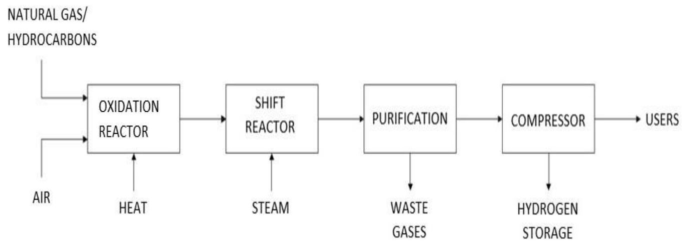

Fig -2: Partial Oxidation of Hydrocarbons

The methods listed above viz., Steam reforming, gasification and partial oxidation produce hydrogen that is classified as **'grey hydrogen'**. Grey hydrogen is defined as hydrogen which when produced leads to the emission of Greenhouse gases such as Carbon monoxide (CO), Carbon dioxide (CO_2), etc. which are released into the atmosphere.

3.4 Carbon Capture and Sequestration (CCS)

It can be observed that the production of hydrogen from the above-mentioned methods leads to the formation of a high amount of Greenhouse gases (GHG) with a large amount of it being in the form of Carbon Dioxide (CO_2). In order to reduce the amount of Carbon Dioxide that is released into the atmosphere and thus contributing to global warming, a technique to enable storage of this Carbon dioxide (CO_2) after production was invented. This is known as Carbon Capture and Sequestration (CCS).

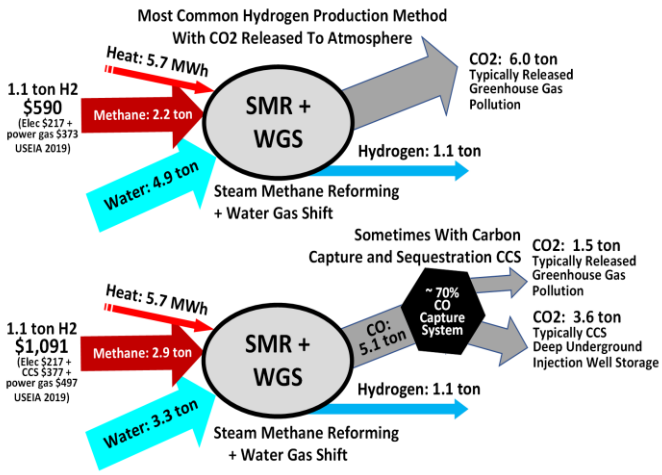

Fig -3: Comparision of SMR with CCS and without CCS

It can be observed from the above figure that production of hydrogen in the absence of a carbon capture system leads to the emission of 6 tons of CO_2 for every 1.1 ton of hydrogen that is produced while utilizing 4.9 tons of water and 2.2 tons of methane in the process. In the second case, it is observed that by utilizing 2.9 tons of methane and 3.3 tons of water leads to the formation of 1.1 tons of hydrogen and 5.1 tons of Carbon Monoxide. With the implementation of a CO Capture system, around of 70% of the CO is captured by the CCS system. Thus, 3.6 tons of CO_2 produced from the process could be sequestered deep underground in naturally occurring geological formations such as depleted gas fields. Only 1.5 tons of CO_2 is released into the atmosphere in the form of GHG emissions which is a substantially smaller amount when compared to a hydrogen production system without the implementation of a carbon capture system while producing the same amount of hydrogen. The hydrogen produced by this method is known as '**blue hydrogen**'. [9]

The CCS system can also be implemented in 2 different ways. The first method is to only capture the CO_2 produced from the steam reforming process. The second method is to capture the emissions from the SMR process as well as the flue gas produced by the combustion of natural gas which is then utilized to run the SMR process.

While blue hydrogen has a smaller carbon footprint as compared to gray hydrogen, another point of comparison is the amount of emissions from using hydrogen fuels as compared to the emissions obtained from the use of other fossil fuels. Various studies that have been conducted over the past years have lead to conclusions stating that the use of hydrogen as a fuel lead to the emissions of at least the same amount of GHG emissions as other fossil fuels and in some cases even more than that.

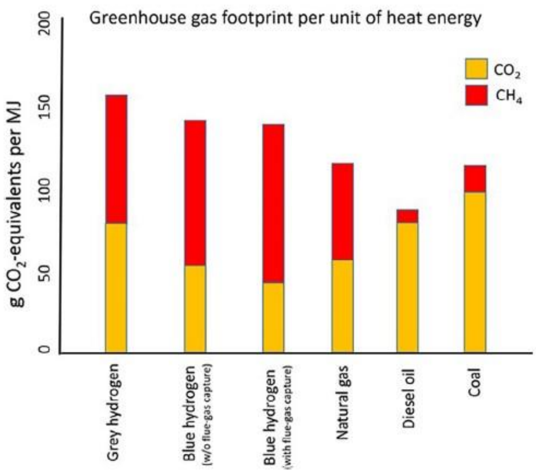

Fig -4: GHG emissions by various fossil fuels and hydrogen [15]

From the above graph, it is observed that while the CO_2 emissions from the use of blue hydrogen is lesser than the fossil fuel alternatives, its overall GHG footprint is greater than the others. Grey hydrogen has the largest GHG footprint. Production of hydrogen by the CCS process leads to a reduction in the CO_2 emissions but the CH_4 emissions remain the same. If a flue gas capture system is also implemented, the CO_2 emissions reduce further and can be observed to be the lowest above. [9][15]

3.5 Methane Pyrolysis

In all of the previously discussed methods of hydrogen production, it has been observed that production of both grey hydrogen and blue hydrogen led to the emission of Greenhouse Gases in the form of Carbon Dioxide (CO_2) and Methane (CH_4). As reducing our GHG emissions and consequently reducing Global warming is of utmost priority, a new method was required to be able to produce hydrogen without the accompanying Greenhouse Gas emissions. This method is known as Methane pyrolysis.

As the name suggests, methane undergoes a process of pyrolysis which leads to the formation of hydrogen gas. Pyrolysis, also known as devolatilization, is the process which causes thermal decomposition of materials at high temperatures. For the production of hydrogen, methane is the chosen material for thermal decomposition. Methane is placed in reactor filled with catalytically active molten metal known as the 'bubble column'. The methane molecules enter from the bottom of the column through a very fine and porous structure in the form of 'methane bubbles'. The methane molecules then react with the catalytically active molten metal to breakdown into hydrogen gas, which then rises up to the top of the reactor where it can be collected and solid carbon which can be collected from the surface of the molten metal. The reaction can be written as-

$$CH_4(g) \rightarrow C(s) + 2H_2(g)$$

Unlike grey or blue hydrogen, the solid carbon obtained from this method does not lead to the pollution of the environment and instead can be used in various industrial applications, or it can be placed in a landfill. The hydrogen produced through this method is known as **'turquoise hydrogen'** and this method is considered to be a non-polluting method of hydrogen production. [16][17][18]

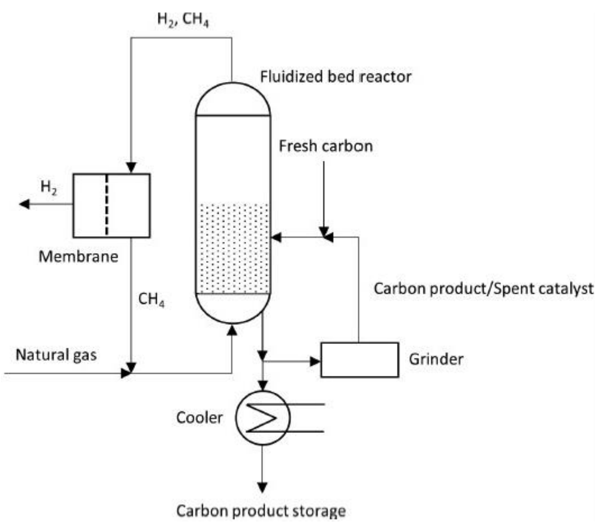

Fig -5: Fluidized-bed reactor setup using a carbon catalyst. [16]

This process is a relatively new process to produce emission free hydrogen and is currently being further studied by various academic teams around the world to study the feasibility of this process for the production of industrial scale hydrogen.

4. Electrolysis of Water

Electrolysis of water is the process of splitting the atoms in a molecule of water into their fundamental elements of hydrogen and oxygen. Compared to the methods discussed in this paper, Electrolysis of water does not require natural gases for the production of hydrogen. Instead, it utilizes the abundantly available Water (H_2O) to produce hydrogen.

Electrolysis is carried out by using electricity to split a water molecule into its fundamental elements - hydrogen and oxygen. The reaction at the anode is given by-

$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$

The reaction at the cathode is given by-

$4H^+ + 4e^- \rightarrow 2H_2$

The overall reaction for electrolysis of water is given by –

$2H_2O \rightarrow 2H_2 + O_2$

From the above reaction, it can be observed that performing electrolysis of water leads to the formation of Hydrogen gas (H_2) and Oxygen gas (O_2). No polluting substances are obtained as a byproduct of this process. The electricity required to carry out electrolysis of water can be provided from any means possible. Thus, the electricity can be produced through solar, wind, or other renewable sources of energy. As no GHG are emitted in the process and if the electricity to undertake the process if provided through renewable sources of energy, then this process can be classified as an emission-free process of hydrogen production. Thus, the hydrogen obtained from completely renewable sources is termed as **'Green Hydrogen'**.

To carry out electrolysis, 3 different types of cells are available. They are-

• Solid Oxide Electrolyser Cells (SOEC)

• Polymer electrolyte membrane cells (PEM)

• Alkaline electrolysis cells (AEC)

Alkaline Electrolysers (AEC) are considered to be the cheaper option as they use nickel catalysts, but they are also less efficient as compared to the Polymer Electrolysers (PEM) which use platinum group catalysts which are much more expensive than nickel catalysts.

4.1 Polymer Electrolyte Membrane Cells (PEM)

Polymer electrolyte membrane cells (PEM) consist of an anode and a cathode. Between the anode and the cathode, a membrane capable of conducting protons is placed. The most commonly used membrane is made of perfluorosulfonic acid polymer and is usually made with a thickness of 50–175 µm. The cathode of the PEM is usually constructed using a porous carbon-based element such as paper or cloth covered with coating of Platinum (Pt) or Carbon (C). The anode is constructed using a porous metallic element such as Titanium (Ti) and is covered with a coating of a noble metal catalyst such as Iridium (Ir) or Rubidium (Ru). Once the electrolyte is constructed an electric current has to be passed to start the process of electrolysis. Upon the application of electricity, the water molecules are broken down into oxygen and protons. The protons are then circulated through the permeable membrane, and they are then converted from protons into hydrogen atoms at the cathode. The hydrogen can then be collected from the cathode side of the electrolyser. As this process is generally operated at temperatures below 100^0C, it is also known as a low-temperature electrolysis. [9][19]

The PEM cells are used in place of the AEC cells due to various reasons such as-

• The alkaline solutions present in the PEM systems require no replenishment and hence the cost of maintaining a PEM system is low.

• The presence of a metallic layer on the anode side of the system, titanium in this case, leads to the formation of hydrogen at higher pressures than that obtained by using AEC systems.

• As the membrane in the PEM system is made of a solid-state polymer, the possibility of gases, such as oxygen, being able to move through the membrane is significantly reduced and thus, hydrogen of very high purity (>99.99%) can be obtained through this process. [9][19]

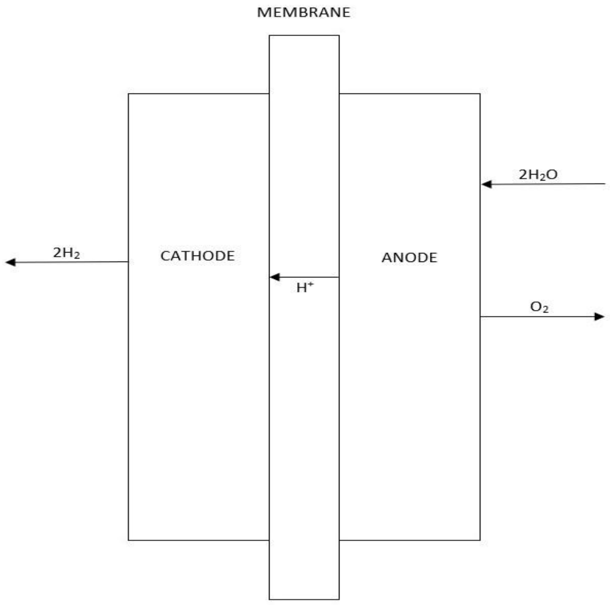

Fig -6: PEM Electrolyser Setup

4.2 Solid Oxide Electrolyser Cells (SOEC)

Solid Oxide electrolyser cells (SOEC) work on the principle of a regenerative fuel cell. It is carried out by conducting electrolysis of a solid oxide or an electrolyte which results in the formation of hydrogen gas at the cathode and oxygen gas at the anode. As this process is carried out at temperatures higher than 500^{0}C, it is known as high-temperature electrolysis. By carrying out electrolysis at higher temperatures, some of the energy required to carry out electrolysis is provided in the form of heat energy which is cheaper than electrical energy. Thus, SOEC systems can achieve higher theoretical efficiencies as compared to low-temperature systems.

A SOEC cell is constructed in a similar manner as the PEM cell. A solid oxide electrolyte is placed between an anode and a cathode. The material of this solid oxide electrolyte determines whether the electrolyte transmits oxide ions or protons.

Thus, SOEC systems can be classified into 2 types-

• Oxide ion (O^{2-})conducting systems

• Proton conducting systems

Oxide ion conducting systems are the more commonly used systems as the proton conducting have not been researched enough and have a lot of disadvantages when compared to Oxide ion conducting systems. [19][20]

4.3 Oxide ion conducting systems

These systems consist of oxide ion conducting ceramic based electrolytes. The most commonly used electrolyte consists of Zirconia Dioxide (ZrO_2) which is partially or fully doped with Y_2O_3 or Sc_2O_3 to stabilize the electrolyte. These are known as YSZ or ScSZ respectively, depending on the stabilizing element used. Apart from ZrO_2 based electrolytes, materials such as Ceria, aka Cerium Oxide (CeO_2), doped with Gadolinium Oxide (Gd_2O_3), known as GDC, or Ceria doped with Samarium Oxide (Sm_2O_3), known as SDC, are also used. GDC and SDC are generally used with a very thin protective covering of YSZ or ScSZ around them. This is done to prevent GDC and SDC from developing electronic conductivity which they generally undergo in reducing atmospheres.

While choosing an electrolysis system, the ionic conductivity of the electrolyte plays a crucial role in determining the efficiency and costs of the system. An electrolyte with a high ionic conductivity permits the use of electrolytes with thickness ranging from 50–200 μm. However, for materials having a low ionic conductivity, an extremely thin electrolyte has to be used with its thickness being in the range of 10 μm. Being so thin, these electrolytes are unable to hold the cell and are hence required to be reinforced with electrodes which adds a significant cost to the construction of these systems.

The cathode is generally constructed of nickel electrodes doped with YSZ or GDC/SDC. These composites have been observed to provide good performance in the initial stages of their use, but they tend to undergo oxidation which results in the formation of Nickel Oxide (NiO) leading to degradation of the electrode. Another commonly used material is Perovskite-type lanthanum strontium manganese (LSM). Studies recently conducted have observed that by doping LSM with scandium to form LSMS helps promote the mobility of the oxide ions within the cathode which then helps in having increased performance when compared with LSM cells at lower temperatures. Further studies conducted have also concluded that materials such as lanthanum strontium manganese chromate (LSCM) have proven to be more stable under their application in electrolysis due to their high redox stability. These materials being rare earth elements add a significant cost to the development of the electrode but also provide better efficiencies than the nickel-based electrodes.

The anodes are constructed using lanthanum strontium manganese (LSM). They are generally doped with some electrolyte material like GDC or YSZ to improve the mechanical properties and performance of the electrode. [9][19][20][21]

The chemical reactions constituting the process are as follows-

Anode: $2O^{2-} \rightarrow 2O_2 + 4e^-$

Cathode: $2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-}$

Net Reaction: $2H_2O \rightarrow 2H_2 + O_2$

5. Hydrogen Economy

The hydrogen economy is defined as an economy where hydrogen fuel replaces fossil fuels in all sectors of the economy. Hydrogen fuel, on combustion, leads to the emission of water vapor, unlike fossil fuels which when combusted lead to the emission of Greenhouse Gases (GHG). Thus, in order to reduce the GHG emissions and help limit the rise of Global Warming, a shift to hydrogen economy is paramount.

In order to change the economy from a fossil fuel-based economy to a hydrogen based one, it is required to switch to hydrogen fuels in 3 main sectors. They are-

• Hydrogen used in the industry

• Transportation sector

• Commercial and residential Buildings

5.1. Industry

A large majority of the hydrogen being currently produced in the world is being used for the purpose of industry. Various process require the use of hydrogen such as production of ammonia, refining oil, methanol production and various other products. However, most of the hydrogen is currently being produced by the use of fossil fuels and is classified as grey hydrogen. Thus, hydrogen production leads to a substantial amount of GHG emissions, which contribute to the ever-rising problem of Global Warming.

In order to reduce the GHG emissions from the production of hydrogen, a shift to producing hydrogen using emission free methods would be the logical step. Using methods discussed in this paper such as Methane Pyrolysis or Electrolysis of water would lead to the production of green hydrogen. This would help in substantially reducing the carbon footprint of the hydrogen production sector.

5.2 Transportation Sector

The most promising use of hydrogen comes in the form of the transportation sector. With emissions from the transportation sector being one of biggest contributors to the GHG emissions per year. In order to meet the target, set by the Paris agreement of reducing the average rise in global temperatures to below 2^{0}C, GHG emissions from the transportation sector will have to be drastically reduced by 2050. In the current scenario, the largest contributing factor to the GHG emissions from the transportation sector is the emissions from fuel consumption. In order to reduce these emissions, a variety of methods have been tested such as Hybrid Electric Vehicles (HEV's), Battery Electric Vehicles (BEV's), Plug-in Hybrid Electric vehicles (PHEV's) and Fuel-cell Electric Vehicles (FCEV's).

In the study conducted by Georg Bieker, it is observed that the life-cycle GHG emissions of BEV's are comparatively lower than the life-cycle emissions from Internal Combustion Engine vehicles (ICEV's). For Europe, the life-cycle emissions of BEV's are ~70% lower than that for ICEV's. They are ~65% lower for the United States, ~41% lower for China, and ~26% lower for India. This suggests that phasing out ICEV's would be the next logical step in order to reduce the GHG emissions from the transportation sector.

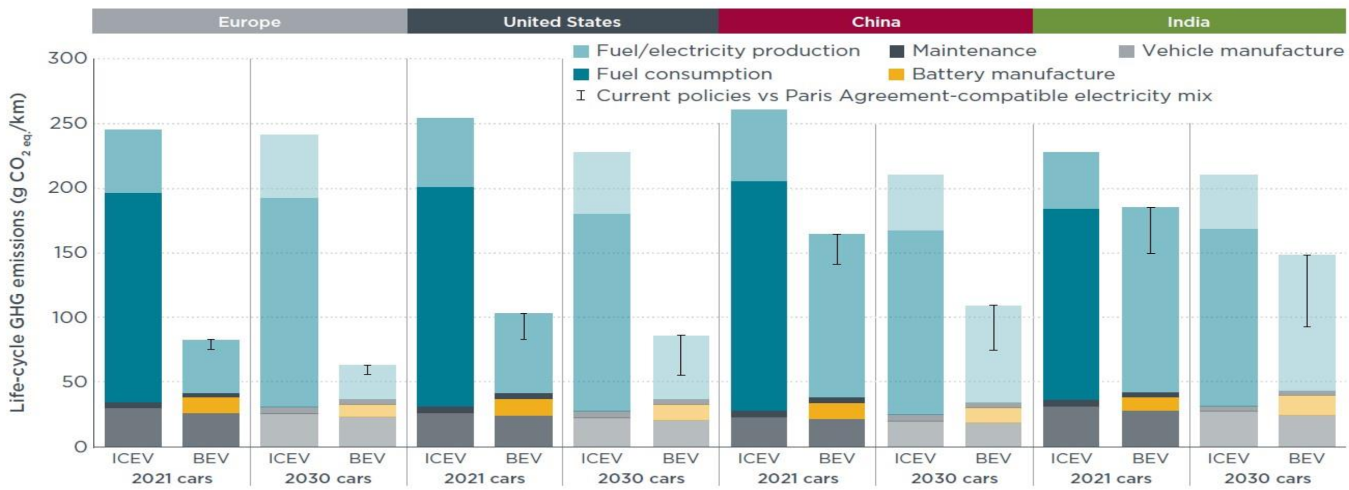

Fig -7: Study conducted by Georg Bieker[25]

In order to limit emissions, elimination of emissions from fuel consumption takes the highest priority. In order to phase out emissions from fuels, fossil fuels should be replaced with fuels generated from renewable sources or energy and which do not lead to emissions upon consumption. The leading alternatives for fossil fuel-based vehicles are BEV's, which run on electricity provided from batteries and thus do not lead to any emissions, and FCEV's, which utilize electricity provided from a fuel cell running on hydrogen.

Hydrogen Powered FCEV's are able to only produce 26-40% lesser emissions than the ICEV's. This is not because of FCEV'S emissions being higher than that for BEV's, but it is because of the method of hydrogen production currently being utilized for the production of hydrogen. As discussed in this paper earlier, a large majority of the hydrogen being currently produced is being produced as grey hydrogen. These processes lead to the emission of a large amount of Greenhouse Gases and thus limit the potential of FCEV's. If the hydrogen was to be produced as green hydrogen, FCEV's would produce ~80% lower life cycle emissions as compared to ICEV's. This would be a substantial decrease in GHG emissions and would help promote the use of Hydrogen powered FCEV's as an alternative to ICEV's.

5.3 Commercial and Residential Buildings

In the commercial and residential buildings, energy is used for a variety of purposes. Energy is provided in the form of electricity to run the various electrical systems of the building. Heat energy is provided for the heating of the building during cold weather. Natural gas is provided for cooking. This energy is provided from a variety of production methods. Electricity is generated from renewable as well as non-renewable sources of energy. Combustion of natural gas is carried out for the heating of the buildings. All of these services can be carried out by using hydrogen as the source of energy. Electricity can be generated using hydrogen fuel cells in a similar manner in which they are used in FCEV's. Heating can also be facilitated by the combustion of hydrogen to generate heat energy. By switching the non-renewable sources of energy to a renewable source of energy in the form of hydrogen, GHG emissions could be reduced substantially.

6. Fuel-Cell Electric Vehicles (FCEV)

A FCEV is a vehicle that runs on electricity. However, the key difference between an FCEV and a BEV is that a BEV works on electricity that is stored in a battery pack. This electricity is provided from an external source and may be generated from a renewable or a non-renewable source of energy. A FCEV on the other hand works on electricity that is generated within the vehicle itself. This electricity is generated by the process of reverse electrolysis where hydrogen and oxygen react to form energy. The only emission from this process is the water vapor which is not a GHG. Thus, FCEV's can be classified as a net zero emission vehicle. The general architecture of a FCEV is shown as-

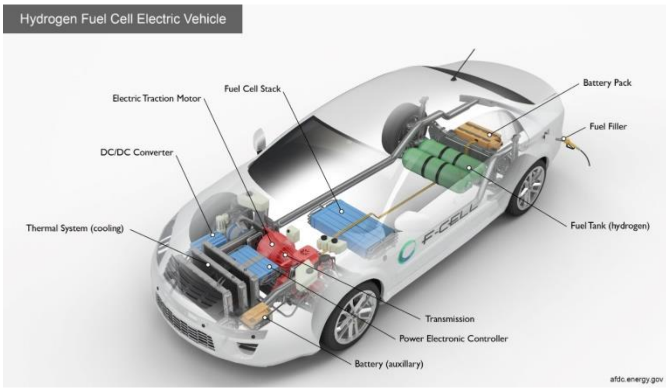

Fig -8: FCEV Architecture[26]

6.1 Main components of a FCEV

Fuel tank - The fuel tank of an FCEV, like an ICEV, is responsible for the storage of the fuel on which the vehicle operates. In the case of FCEV's, the fuel to be stored is hydrogen. Hydrogen is stored in its liquid form to be utilized by the fuel cell as and when required. The Fuel tanks are constructed of thick-walled tanks that do not run the risk of explosion if hydrogen comes in contact with oxygen.

Fuel cell stack - The fuel cell stack is the main powerhouse of the FCEV. The Fuel cell stack is an assembly of a number of electrodes which carry out electrolysis in order to generate electricity. The hydrogen is provided from the fuel tank and the oxygen is taken from the atmospheric air. The number of fuel cells is directly proportional to the power of a FCEV. Thus, in order to manufacture FCEV based heavy vehicles such a buses or trucks, the only change would be to increase the number of fuel cells and thus increase the power output of the vehicle.

Battery pack - The battery pack is utilized to store excess energy that is generated in the vehicle. This energy can be in the form of electricity obtained from regenerative braking, or electricity produced by the Fuel cells, but which is currently not required by the Vehicle.

Electric motor - An electric motor is utilized to convert the electrical energy into mechanical energy and drive the wheels. It can obtain the electrical energy from the battery or directly from the fuel cells depending upon the requirement.

6.2 Working of a FCEV

From the diagram above, it can be observed that there are 3 different flows present in the FCEV. They are the hydrogen, electrical and the propulsion (mechanical) flows. First, hydrogen is filled into the FCEV through the filler. This hydrogen is stored in the hydrogen tank in the liquid form. -Once the requirement arises, the hydrogen is transported from the hydrogen tank to the fuel cells. Here, reverse electrolysis is carried out with hydrogen obtained from the fuel tank and oxygen obtained from the atmospheric air. This electrolysis results in the formation of electricity and water vapor. The water vapor, being innocuous to the environment is released through the tailpipe.

The electricity produced in the fuel cells can either be stored in the battery pack or it can be directly transmitted to the electric engine in order to drive the vehicle. The electric engine, which consists of an electric motor and a transmission is tasked with converting the obtained electrical energy into mechanical energy. This mechanical energy is then provided to the wheels of the vehicle. If the demand for electrical energy by the electric engine is high, then the battery can also provide the engine with the energy stored in the battery. The electrical energy harvested from regenerative braking is also stored in the battery.

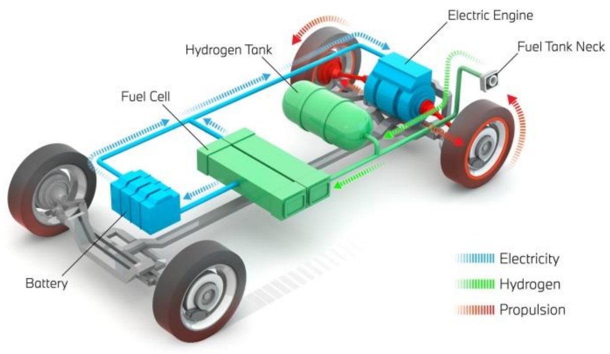

Fig -9: FCEV Energy transfer[27]

6.3 Advantages of FCEV

The recharging time for BEV's is currently between 30 mins to several hours depending on the car model and the charging infrastructure being used. FCEV's, on the other hand, can be filled up with hydrogen fuel in the same way as a gasoline powered car and this can be achieved in 5 minutes. Thus, FCEV'S are much more convenient as compared to BEV's.

Another advantage of FCEV's is their range. FCEV's typically have a range of 300 miles or 480 kilometers. Honda has claimed for their Clarity FCEV an estimated range of 360 miles or 580 kilometers. Hyundai has claimed for their NEXO has 333 driving range of 413 miles or 665 kilometers. These figures are also achievable in BEV's but to achieve this, larger battery sizes would have to be utilized which would then lead to an increase in the weight of the vehicle as well as the charging times.

6.4 Disadvantages of FCEV

The biggest disadvantage of FCEV's currently is the lack of hydrogen refueling stations. While electric car charging stations can be found as frequently as a gas pump, hydrogen refueling stations are sparse. At the end of 2019, The US had around 40 hydrogen refueling stations compared to the 80 present in Germany. But these are still a long way short of the number of gasoline and electric car charging stations.

Another disadvantage of FCEV's is their high cost. A FCEV could cost up to 2 times the cost of a comparable BEV. This issue has led to the low demand for FCEV's. The high prices can also be attributed to the fact that FCEV's are currently not in mass production stage and thus the production costs could come down significantly when mass production of FCEV's is put into place. The prices of hydrogen are also higher compared to electric vehicles. In the US, 1 lb. of hydrogen costs around USD 14. A typical FCEV can drive up to 28 miles on 1 lb. of hydrogen. This is significantly higher than the cost to run a BEV for the same distance.

7. CONCLUSION

The potential of a hydrogen economy is unignorable. In order to meet the targets, set in the Paris agreement, hydrogen will play a key role in helping us achieve those targets. The advantages of hydrogen as a fuel over conventional fossil fuels are astonishing. Undertaking production of hydrogen through renewable sources of energy should be of utmost priority. Reducing the cost of green hydrogen will open a multitude of paths for the foundation of a hydrogen economy. Using hydrogen as a fuel for FCEV's brings with it a lot of advantages over conventional ICEV's and BEV's with its sole setback being the cost to run a FCEV.

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