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Hydrogen Energy as a Versatile Solution towards Greener Future for Sustainability

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***Abstract*— Growing population of the world demands higher energy requirements without affecting environmental balance. Fossil-fuels making pollution will soon get exhausted with its limited stocks. Hence it is required to find an alternative for clean energy production. Here green energy technology refers to the acceptable solution where utilization of renewable and sustainable energy sources helps to generate power while minimizing environmental impact. Solar energy, bio and geothermal energy, tide and wave energy, wind and hydro energy are some common substitutes of degrading energy sources having lots of benefits as well as the drawbacks in the output. However, production-wise these are not sufficient to cater the energy need of the modern civilization where hydrogen fuel cell is considered to be one of the most promising energy resources to lead the field in coming decades. The primary source of hydrogen exists in fossil fuel form as natural gas. The availability of hydrogen makes it possible to fulfill future global energy demands sustainably. So this paper includes a brief discussion on 'hydrogen energy' as a resource of the future. If hydrogen produced from renewable sources is synthesized with captured carbon-di-oxide in a biomass power plant, then it benefits in carbon neutrality and energy security. This hydrogen energy can be useful to enhance the energy efficiency alongside it provides overwhelming environmental and social benefits creating economic opportunities as well. Nevertheless, along with numerous advantages of hydrogen energy, some limitations may sometimes rove to be extremely fatal.**

***Keywords*—Fossil Fuel, Hydrogen Fuel Cell, Carbon Neutrality, Renewable Energy.**

I. INTRODUCTION

Population of India is ever-increasing in line with the world- wide trend. The required energy for modern civilization mostly comes from traditional fossil fuels through coal mining and oil extraction which leads to environmental degradation and habitat destruction [1]. Available fossil fuels are also not enough to supplement all energy needs of the global population including one hundred forty crores of India. Also due to the burning of fossil fuels, carbon dioxide, carbon monoxide and other harmful green-house gases radiates in the nature which goes against the Paris agreement (2015) (https://tinyurl.com/77288v3j). So the target is to reduce greenhouse gas emission and the development of nature- friendly energy resources utilizing the current technological advancements which are the need of the hour. There are a few such natural energy resources commercially available for last few decades and their availability is noticeable in various forms, such as solar, hydro, wind, geothermal, tide and wave. Though they are environment friendly, they have some limitations. Installation cost of solar energy is very high, not available throughout the day and in all seasons and it cannot be used in rural areas [2]. For hydro energy, a dam needs to be created which leads to demolition of habitat and also it can lead to severe flood during monsoon in the nearby areas. Wind energy production amounts less energy and production is only accountable /possible in open ground area, preferably near sea shore. Geothermal energy requires high initial cost, it is location specific and can initiate the seismic activities causing earthquakes producing instability along the fault or fracture lines. Tide and wave energy require high production cost and may cause severe damage to the marine life [1]. So as the reliable guides towards greener future, the hydrogen and methanol energy have been identified to play their important role. Hydrogen serves as a clean alternative to both methane and other dangerous gases in the same way natural gas does. Hydrogen exists naturally on Earth as the abundant liquid form of water and glaciers. However, in its gaseous form it is very scarce, volumetrically less than 1 part/million. But it shows a very high energy efficiency of 120 MJ/kg compared to that of the diesel, whose energy density is only 45.5 MJ/kg. So the efficient production and utilization of hydrogen energy in different sectors through hydrogen fuel cells appears as one of the evolving areas in the energy research field. Other than water vapour, here no methane or any other toxic gases emit to cause air pollution, can be used in remote areas causing reasonable democratization of power supply. Present work is an endeavour to highlight such possibilities considering the technical viabilities with the expected outcome from various perspectives.

II. MATERIALS & METHODS

Hydrogen is invisible in gaseous form and emits only water and heat when burned. But producing it may be carbon intensive depending upon the methods. Grey hydrogen is generated from natural gas or methane through steam-methane reforming, without capturing the greenhouse gases produced as a byproduct. De-carbonized hydrogen is Blue hydrogen and produced by natural gas reforming technique coupled with carbon capture and storage (CCS). So grey hydrogen is as same as blue hydrogen, excepting the use of CCS [3]. Therefore, blue hydrogen enables large-scale production of low-carbon hydrogen and it supports decarbonization efforts in the transportation sector. This makes it a key solution for reducing carbon emissions. It is significantly cheaper than green hydrogen which is obtained from electrolysis by passing electricity through water and getting hydrogen separated. People use hydrogen and vent the oxygen to the atmosphere with no negative impact. But blue hydrogen depends on natural gas which makes it a subject to high price volatility and geopolitical turbulences. As green hydrogen is produced in a manner which is climate-neutral, it could contribute to the global efforts in reducing carbon emissions to net zero by 2050 [3]. Here we discuss about some methods of hydrogen production step by step.

A. Steam Methane Reforming:

In this process, the chemical energy stored in methane is converted to another form of hydrogen energy,

B. Units required:

- Desulfurizing unit
- Reforming unit
- Shift reactor
- Separation unit

C. Reactions:

$CH_4(g)+H_2O(g)\rightarrow CO(g)+3H_2(g)$

$CO(g)+H_2O(g)\rightarrow CO_2(g)+H_2(g)$

The first reaction absorbs heat as an endothermic process (+251 MJ/kmol) while the second reaction releases heat as an exothermic process (- 41.2 MJ/kmol). The overall process operates as an endothermic reaction. The reformer operates at 700–1000°C with 15–50 bar pressure while using 2 to 5 steam-to-carbon ratios for methane-steam reactions. The high-temperature reformer generates a product gas that needs cooling before proceeding to the second stage of steam methane reforming in the water gas shift membrane reactor. The syngas leaving the shift reactor contains hydrogen, unreacted carbon monoxide, carbon dioxide, water, and traces of natural gas. This gas mixture is the result of the reforming process. The first step of hydrogen production involves moisture removal through condensation. Then the hydrogen is separated.

D. Electrolysis:

The electrolyzer uses electricity for breaking water molecules into hydrogen and oxygen gas. The electrolyzer contains two electrodes known as an anode and cathode. Their separation is caused by an electrolyte. There are three types of electrolyzer:

1) *Polymer Electrolyte Membrane Electrolyzer:* The electrolyte exists as a solid material in this system. The anode causes water to break down into oxygen and positively charged hydrogen ions (protons). The external circuit allows electrons to pass through while hydrogen ions move across the PEM to reach the cathode. At the cathode, hydrogen ions combine with electrons to form hydrogen gas.

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

Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$

2) *Alkaline Electrolyzer:* The electrolyzers operate with liquid alkaline solutions of sodium or potassium hydroxide as their electrolyte. The electrolyte transports hydroxide ions (OH-) from the cathode to the anode while producing hydrogen at the cathode side.

3) *Solid Oxide Electrolyzer:* The electrolyte material consists of solid ceramic which enables the transport of negatively charged oxygen ions (O^2). The cathode takes in steam, which combines with electrons from an external circuit. This reaction produces hydrogen gas and negatively charged oxygen ions. The oxygen ions move through a solid ceramic membrane toward the anode. At the anode, the ions form oxygen gas. This process also generates electrons that flow back to the external circuit.

The chemical reaction in fuel cells uses grey hydrogen to produce power. The hydrogen fuel cell contains hydrogen and oxygen atoms which have their anode exposed to hydrogen while their cathode faces air. The energy production occurs through hydrogen oxidation reaction and oxygen reduction reaction. The cathode material consists of Cobalt-manganese. The cell reactions require platinum and iridium as their catalysts. The reaction anode contains these catalysts which split hydrogen molecules into protons and electrons that proceed to the cathode through separate paths. The electrons generate electricity through an external circuit as they pass through [[4], [11], [13], [14]].

III. RESULTS AND DISCUSSION

Hydrogen fuel cells are easily chargeable and can supply a huge amount of energy in various sectors, particularly to mention, the transportation in land, in air and under-water, in space craft, in industry and in daily life and are represented in Table 1 along with its producers.

TABLE I. APPLICATION OF HYDROGEN FUEL

Serial no	Application of Hydrogen fuel		
	Application sector	***Uses***	***Hydrogen procedures***
I	Household appliances	Hydrogen fuel cells can be used in small household appliances like TV, radio, mobile etc. Hydrogen fuel cells are easily chargeable and it can supply a huge amount of energy.	LINDE: It has more than 160 refueling stations worldwide. Linde provides constructions, installation of pipelines, equipment for hydrogen transportation
II	Vehicle fuel	Effective alternative to reduce pollution as hydrogen energy does not release any harmful gases. Presently, Hyundai Nexo, Toyota Mirai, Honda Clarity use hydrogen fuel cells which later may be used in public transports and even trucks.	PRAXAIR: It is one of the leading companies for producing hydrogen. They supply compressed and liquid hydrogen of various concentrations.
III	Rocket fuel	The production of high-energy output depends on liquid hydrogen. The shuttle's main engine operates with liquid hydrogen because this fuel enables the production of the massive upthrust required for rocket launch.	FUELCELLENERGY: This company undertakes project to install, operate large-scale fuel cell systems and provides energy output.
IV	Powering aircraft and Auxiliary Power Units (APUs)	Hydrogen fuel cells are a great un-contaminating alternative of jet fuels. The system provides a dependable and efficient power source which enhances aircraft safety and operational performance. The hydrogen fuel cells enable the operation of Transport Refrigeration Units (TRUs) which maintain cold food storage inside the APU. It also provides power for air conditioning.	H2SCAN:HY-OPTIMA which process hydrogen analyzers and HY-ALERTA which detects hydrogen leaks are developed by this company. The products have been used in various organisations to avoid any type of fatal.

V	Use in submarines	Nowadays hydrogen fuel cells are used in German submarines like Type212A and Type212CD. Hydrogen fuel cells are more power efficient than other energy sources. These can provide longer range and silent cruising.	SAGIM: It is specialized for manufacturing of hydrogen production units. It is present in more than 90 countries.
VI	Industries	Hydrogen Fuel Cells can generate huge amount of energy in comparison with other energy sources, so this fuel cells can be used in large industries like food industry, clothes industry.	ADITYA BIRLA CHEMICALS: It is a supplier of epoxy, phosphates, sulphites and producer offluorides, fertilisers.

There are several challenges [[5], [8], [9], [12], [16]] of using hydrogen fuel cell:

1) Storage and delivery of Hydrogen: Hydrogen is a very light weight gas, which is stored at high pressure and low temperature of -253°C making the storage and delivery process troublesome.

2) Safety measures: The flammability of hydrogen becomes high when it burns in air at concentrations between 4% and 75%.

3) Expensive raw materials: Metals like platinum and iridium are used as catalysts in hydrogen fuel cells which makes it costly.

4) Insufficient fueling stations for vehicles: The number of fueling stations and charging points are very less. This takes the whole gain ground process to a cease.

5) Waste and heat generation: Some amount of waste and heat are produced during the cell reactions.

Working out on the challenges [5]:

- The use of Nitrogen-doped carbon coated nickel as catalysts instead of platinum and iridium, which will be much cost effective, can be ensured.
- Proton Exchange Membrane Fuel Cell can also be used as it generates less amount of waste.
- Heat produced during the cell reactions can be converted into other energy and can be used in several sectors.
- More number of charging points are needed to make the market of hydrogen fuel cell vehicles grow.

But the key challenges are its safe storage and transportation [[5], [6], [7], [10], [15]]. The storage of hydrogen occurs through three methods which include compression and liquefaction and solidification. The storage of hydrogen requires Type III and Type IV tanks which maintain high pressure to store the gas. These are light weight but costly. The inner winding of Type IV tank is made of polymer and outer winding with fiber. Honda Clarity and Toyota Mirai uses pressurized vessel-based storage where hydrogen is stored at 700 bars. Moreover, the process of compressing hydrogen to such high pressures requires significant energy which reduces the overall efficiency of this storage method.

Liquid hydrogen storage requires cooling hydrogen to cryogenic temperatures (approximately -253°C). While this approach increases volumetric energy density, it presents challenges such as significant energy consumption for liquefaction and the need for well-insulated tanks to minimize boil-off losses. In case of liquified hydrogen it uses a container with high insulation to protect from heat intake. But in some cases when pressure is formed the evaporated hydrogen is released to maintain the pressure.

Cryo-compressed tanks (combination of compressed and liquid state storage) can store hydrogen at 70-200K temperature. BMW uses cryo-compressed tanks for energy production.

The storage of hydrogen occurs through chemical reactions between metals or alloys and hydrogen which produces metal hydrides. The storage method enables hydrogen to be stored at low pressure conditions while operating at room temperature. The weight-to-hydrogen ratio of metal hydride storage systems remains low at 1% which results in heavy systems that are impractical for weight-sensitive applications

The storage of Hydrogen in solid form is also a possibility as it is much safer. Hydrogen is bonded via weak Vander Walls bond in case of adsorption of metals. Compressed gaseous hydrogen can be transported by tube trailer and pipeline and on the other side liquid hydrogen can be transported by cryogenic tankers and LOHC (Liquid Organic Hydrogen Carriers). Depending on the place of transportation distance, quantity of hydrogen and its use, the selection of modes is done. For long distance and large quantity of hydrogen, it is transported using pipelines and LOHC, but for local distribution tankers are preferred. If the hydrogen needs to be used in fertilizer industry, it can be transported in the form of ammonia. Places where pipelines are not available, liquid hydrogen is transferred through cryogenic tankers. But hydrogen is a highly flammable and volatile gas, requiring careful handling and safety measures. It ignites at very low energy levels**,** even from static electricity or a small spark. Hydrogen molecules are the smallest and lightest, allowing them to escape through tiny gaps in pipelines, fittings, or seals. Hydrogen can diffuse into certain metals, weakening their structure over time. This leads to cracking or failure in pipelines, storage tanks, and structural components. For cryogenic hydrogen storage vessels require advanced insulation to prevent boil-off and pressure build up. For compressed hydrogen a sudden rupture can cause catastrophic energy release, leading to explosions or flying debris. So to avoid these condition some precautions should be maintained always for hydrogen handling, including leak detection technology, ventilation systems, use of non sparking tools, strict material selection to avoid embrittlement and moreover advanced insulation and pressure relief systems for cryogenic and compressed hydrogen storage.

Here it may be mentioned that at present India has a demand of 6 MTPA hydrogen. It is expected that by 2040, the green hydrogen's requirement is likely to grow between 15-25 MTPA. But still, this will be only 5% of the total energy consumption. For Green hydrogen production, hubs need to be located in regions where hydrogen is in demand, like- refineries, fertilizer industry. Presently, India spends more than $160 billion/ year for energy (fossil fuel) imports. India can replace fossil fuels by hydrogen energy in transport, iron and steel and large industries. So, by switching to hydrogen fuel India can save $15-20 billion in fossil fuel imports.

IV. CONCLUSION

To produce and use hydrogen energy in a sustainable manner and to progress further, following steps must be considered.

a) Identification of the field for effective use of hydrogen energy is preferable. Here transportation is one of the biggest sectors which uses fossil fuels and needs to be transformed to hydrogen fuel cells to increase its efficiency maintaining the environmental balance. It can provide similar range with higher energy density and is refueled faster.

b) Government needs to be proactive in terms of making policies for creating the infrastructure and the market and also making the public aware of this technology highlighting the cost effectiveness, risk management factor encouraging people accepting this technology.

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