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A Brief Overview of Renewable Hydrogen Production: Prospects and Challenges

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Abstract: **Hydrogen energy is produced by the electrolysis of fossil fuels such as oil, natural gas, or coal. It may also be created using renewable energy sources such as solar, wind, and hydropower to help reduce greenhouse gas emissions. This method of acquiring vast amounts of hydrogen is still being investigated in order to develop a realistic and economical method of manufacturing it domestically.Hydrogen, on the other hand, is abundant on Earth. It is often found as an element in another compound, such as H_2O or CH_4, and must be processed into pure hydrogen before being utilized in fuel cell electric vehicles. H_2 fuel is combined with O_2 from the air in a fuel cell via an electrochemical reaction to generate electricity and H_2O.**

Keywords: **Renewable energy, hydrogen production, Storage and distribution.**

I. INTRODUCTION:

Hydrogen gas is an important energy transporter and feedstock for the industrial applications, and it has the potential to detoxify a variety of contaminants in water. Because it can charge chemical fuel cells, it's very attractive as an energy carrier.Net greenhouse gas emissions must fall to zero and stay there permanently to prevent global warming. Simply put, all emissions must come to a halt or be completely offset by the removal of greenhouse gases (especially carbon dioxide) from the environment. In a future decarbonized environment, hydrogen is frequently seen as a significant energy carrier. Hydrogen is a possible prospect for replacing fossil fuel depletion and greenhouse gas emissions as an alternative fuel (Das et al., 2001; Argun et al., 2009). Various investigations have been carried out rapidly in the last decade in order to develop a sustainable energy source that can replace fossil fuels. Wastewater treatment can be combined with bio hydrogen generation at the same time (Kim et al., 2001). The procedure entails integrating current water treatment systems with multiple technologies such as chemistry, microbiology, and engineering (Preethi et al., 2019)

The majority of hydrogen is created by steam reforming methane in natural gas, which emits a lot of CO_2. Many people are proposing that carbon capture and storage be used to minimize these emissions (Howarth and Jacobson, 2021). Blue hydrogen has the potential to help with climate mitigation due to its low life-cycle CO_2 emissions. It can replace the use of unabated fossil fuels in industrial and energy uses. Hydrogen produced from fossil fuels with Carbon Capture and Storage (CCS) can help reduce Circular Carbon Economy (CCE)(Zapantis, 2021).

Hydrogen may be produced in a variety of ways, from organic sources such as fossil fuels and biomass, as well as inorganic elements such as water. Water may be separated into hydrogen and oxygen using electrolysis or solar energy. Hydrogen may also be produced by biological processes in microorganisms such as bacteria and algae.Many techniques for the efficient synthesis of hydrogen have been described throughout the last few years (Bechelany., et al., 2013).

It is possible to manufacture hydrogen from a wide range of home resources, including fossil fuels and biomass, as well as water electrolysis when electricity is used. The method by which hydrogen is created has an influence on its environmental impact and energy efficiency.

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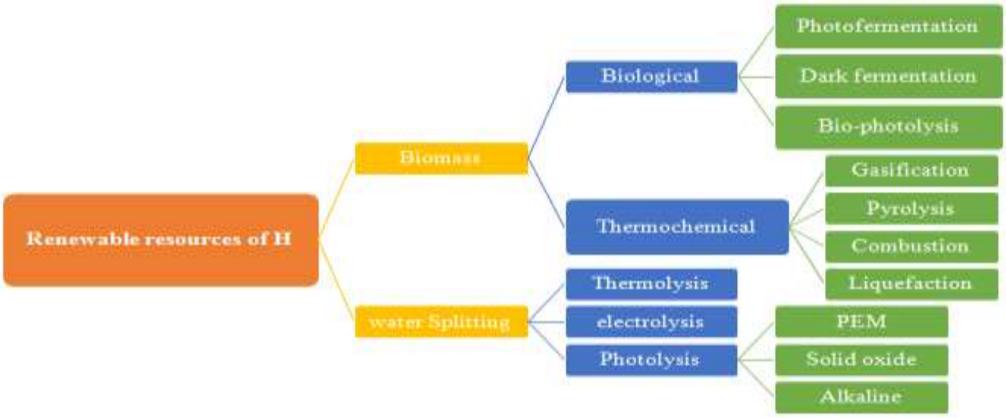

1. Biomass

Biomass may be utilized directly to produce hydrogen through gasification processes. Nevertheless, these procedures are impeded by problems and inconveniencies, particularly when the goal is connected to distributed power generation. The most optimal industrial strategy is to create transportable biofuels or biomass compounds that concentrate a substantial proportion of raw biomass while having a low bulk volume(Panagiotopoulou et al., 2014).

In general, there are two basic routes for solar hydrogen generation from natural gas. The upstream part is similar to a concentrated solar power plant with thermal energy storage till the power cycle. The downstream component is a chemical plant with heat input from natural gas combustion and sun energy. Concentrated solar energy is employed in the indirect technique to generate heat for the che mical plant(Boretti & Banik, 2021). Natural gas includes CH_4, which may be converted into hydrogen by thermal processes like as partial oxidation and SMR. In partial oxidation, CH_4 interacts with a little quantity of O_2, which is insufficient to totally oxidize the hydrocarbons to carbon dioxide and H_2O. The reaction products are principally hydrogen and carbon monoxide (and N_2 if the reaction is carried out with air rather than pure O_2) with a trace of carbon dioxide and other molecules.

Proton exchange membrane fuel cells (PEMFC) are likely to be extensively employed as a power unit for automobiles, home co-generation, and a power unit for mobile goods since the operating temperature is quite low (~120℃) and its start-and-stop regulation is pretty straightforward. Economic and technical constraints are the most common stumbling blocks in the H2 manufacturing process. H2 storage, compressor and distribution networks, shortage of lasting fuel cell technologies, and integrating with the existing infrastructure are examples of financial and strategic challenges that must be overcome before hydrogen can become a viable alternative to fossil fuels (Kumar, et al., 2009). Some biomass feed stock costs too much to process. New ways need to be found to grow and harvest energy crops as well as biomass waste. How to make more H2 by changing the way microorganisms work, how to keep H2 from transferring between species in non-sterile conditions, and how to separate and purify H2 are some of the other problems that need to be solved, as well (Pandu and Joseph, 2012).

1.1 Thermochemical Processes

Certain thermal processes generate hydrogen from their molecular structure by consuming energy from natural gas, coal, or biomass. In several additional procedures, heat is used in combination with closed-chemical cycles to produce hydrogen from feedstocks such as water.

1.1.1. Gasification

Gasification is a non-combustion process that transforms organic or fossil-based carbonaceous products at high temperatures. Hydrogen may be separated from this gas phase using adsorbers or specific separators. Through a water-gas shift process, the carbon monoxide hydrolyzes to generate carbon dioxide and additional hydrogen. Hydrogen may be combined with natural gas to minimize carbon emissions, however there are certain limitations. According to National Renewable Energy Laboratory (NREL) experts, mixing up to 20% hydrogen with natural gas is expected to be viable (NREL, 2021).

$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

1.1.2. Pyrolysis:

The gasification of biomass in the absence of oxygen is known as pyrolysis. Biomass somehow doesn't decompose naturally as easily as coal, and the gas mixture exiting the gasifier contains various hydrocarbon molecules. To make syngas, an additional step must be required to reform these hydrocarbons with a catalyst.

1.1.3 Liquefaction:

Organic wastes may be used to produce cellulosic ethanol, bio-oils, and other liquid fuels. Some of these fluids may be transported for free to a refueling station or another area of

use, where they're being reformed into hydrogen. The following steps are involved in the biofuels fluids to hydrogen reforming process, which is quite similar to natural gas reforming: the liquid fuel is mixed with steam at high temperatures in the existence of a catalyst to make reformate gases, which are mainly H_2, CO, and a trace of C_2O. By combining CO (produced in the previous step) with high-temperature steam, the "H_2O-gas shift reaction" creates additional H_2 and C_2O. The H_2 is finally purified and separated.
Steam reforming reaction (ethanol)

$C_2H_5OH + H_2O$ (+ heat) $\rightarrow 2CO + 4H_2$
$CO + H_2O \rightarrow CO_2 + H_2$ (+ a little amount of heating)

1.2. Biological hydrogen production

Hydrogen gas generated by biological processes is promising since it is ecologically benign and can be produced at room temperature with minimal energy use. Carbon-based gas emissions do not occur during this process, eliminating the requirement for fossil fuels in the manufacturing of the gas (Elam et al., 2003).Due to the ability of employing sunlight, biological techniques of hydrogen synthesis are preferred over chemical methods. Hydrogen gas will be useful not just as a clean energy source, but also as a means of establishing extraterrestrial life. Non-sulfur photosynthetic bacteria such as Rhopseudomonas(Lee et al., 2011) and Rhodobacter are among the eco-friendly bacteria utilized for this purpose. Heterotrophic bacteria may create hydrogen under anaerobic circumstances by fermenting carbohydrate-rich solutions, such as urban and industrial sewage. Photosynthetic bacteria, on the other hand, can help in photobiological H2 generation (biophotolysis) (. The methods of biological hydrogen generation may be divided into fermentation, photo-fermentation, and photo biological hydrogen synthesis, respectively (Manish and Banerjee, 2008; Eroglu and Melis 2011).

1.2.1. Fermentation as a Source of Hydrogen

The production of hydrogen during the fermentation process (Zabut et al., 2006) has lately piqued the curiosity of academics and experts. Many variables influence hydrogenase enzyme activity (Mulin et al., 2004), including pH, temperature, organic diet, feed rate, and solid retention period (Ginkel et al.,2001). It should be noted that these parameters should be evaluated regularly to get better hydrogen production. The pace of fermentation-based biological hydrogen production is great, however the efficiency of conversion from organic substrate to H2 is low.

Anaerobic microbes generate hydrogen gas from organic molecules (Kapdan and Kargi, 2006). Fermentation occurs as biomass develops from the organic substrate during biological hydrogen generation. Because it may continue even in the absence of light, this fermentation has several benefits over other biological hydrogen generation processes like photosynthesis and photo-fermentation(Kraemer and Bagley., 2008).

1.2.2. Photo biological Hydrogen Production

Two enzymes, nitrogenase and hydrogenase, play a critical role in biohydrogen activities. Nitrogenase contains three types of dinitrogenase, which are mostly dependent on the presence of metals. Type one contains Mo(Thiel.,1993), type two contains vanadium(Bishop, et all., 1992) , and type three contains Fe (Kentemich., et al.,1991).
One mole of H_2 is produced for every mole of N2 fixed by the enzyme nitrogenase. Maintaining a cellular redox state is also aided by nitrogenase-mediated hydrogen generation by non-sulfur bacteria (Basak and Das, 2007). Molecular hydrogen is regarded as the ultimate future fuel due to its tremendous energy content and clean conversion to water. Nature has created biological processes that use sunlight to oxidize water (oxygenic photosynthesis) and enzymes that manufacture H_2 (hydrogenases) using electrons (Hemschemeier et al., 2009). Bacteria that have photosynthetic pigments and can photosynthesizes are known as photo-heterotrophic bacteria. The purple non-sulfur bacteria may be able to divert electrons from an organic substrate to hydrogen production. Small organic acids are employed in these techniques, which are generally produced but not digested during fermentation (Harwood., 2008).
The efficiency of hydrogen generation is determined by numerous factors or characteristics, which are particularly significant when large-scale hydrogen production is desired. These factors are Environmental conditions which include Light(Pinzon-Gamez, et al.,2005; Stal and Krumbein.,1985), Temperature(Moezelaar, et al.,1994), Salinity, Micronutrients (Jeffries, et al., 1978), Carbon source (Datta, et al., 2000), Nitrogen source (Lambert, et al., 1979), Molecular nitrogen, effect of S,O and methane on Hydrogen production.
Even while direct bio-photolysis technologies seem to have inherent limits in light conversion efficiency and very time-consuming economics, they nonetheless appear to be promising. Direct biophotolysis is hampered by the use of nitrogenase enzyme, which has a high energy demand and a low conversion efficiency (Pandu and Joseph, 2012).

1.2.3 Dark fermentation

It is capable to producing H_2 in the absence of light. There are no oxygen constraints, and it may generate a variety of metabolites as a by-product (Sen et al., 2008). Because the procedure does not rely on the presence of a light source, it is not impacted by weather conditions and does not need the use of a lot of land or budget (Meng, et al., 2006). In addition to producing useful metabolites such as butyric, lactic and acetic acids as byproducts, it also creates ethanol

(Kapdan and Kargi, 2006). Temperature, pH, HRT (Hydraulic Retention Time), H_2/CO_2 partial pressure, and volatile fatty acids may all influence fermentation(Das and Veziroglu, 2008).

II. WATER SPLITTINGELECTROLYSIS

Electrolysis is a possible method of producing carbon-free hydrogen from renewable and nuclear energy. Electrolysis is the methodology of breaking water into H_2 and O_2 employing electricity. This operation is carried out using an electrolyzer. This technique is classified into two major groups based on the temperature at which water electrolysis is performed: low-temperature electrolysis and high-temperature (Gunduz., et al., 2018) electrolysis. The polymer-electrolyte membrane and alkaline water electrolysis processes occur at a low temperature of 100 °C, while the solid oxide electrolysis cells (Brisse., et al., 2008) electrolyze the water at a high temperature (usually > 600 °C).

1.3. Alkaline water electrolysis

Alkaline water electrolysis was the first marketed water electrolysis system still, this system is the most widely used water electrolysis technique. Electricity is utilized in an alkaline water electrolysis cell to break water molecules into H_2 and O_2 gases. The process of H_2O splitting happens as a result of the half-cell processes described in the scheme (2)(Millet., 2011). Alkaline water electrolysis catalysts are less expensive compared to the platinum metal group-based catalysts used in PEM water electrolysis. Alkaline water electrolysis also has a more significant gas purity and durability due to a mobile electrolyte and reduced anodic catalyst dissolving (Durovic., et al., 2021).

1.4. Solid oxide electrolysis (SOE)

The solid oxide electrolysis cell is the dominant technique for high-temperature electrolysis to produce green hydrogen. The fuel is supplied to the anode (oxidation) in solid oxide electrolysis, while oxygen is given through the cathode (reduction). As shown in Figure 2, oxygen entering the cathode is reduced to oxygen ions, which push through the dense oxide-ion-conducting electrolyte towards the anode and are ruined during the oxidation of fuel to create power (Arunkumar, et al., 2019). The structural criteria of electrodes include a durable chemical configuration, porosity for mass transfer, chemical connectivity, and thermal expansion coefficient match with the electrolyte, and remarkable electrocatalytic activity at the temperature of the SOE procedure (Boulfrad and Traversa.,2014).
Nowadays, the SOE devices are made of ceramic and metallic-ceramic (Baukje., 1998), particularly Ni/Yttria-stabilized zirconia (YSZ) as the anode, perovskite and lanthanum strontium manganese oxide with YSZ as the cathode, whereas YSZ is utilized to confirm the electrolyte (O^{-2})(Atkinson., et al., 2004).

1.5. Polymer-electrolyte membrane (PEM) electrolyzer

Instead of utilizing a liquid, PEM electrolysis uses an ionically conductive solid polymer to initiate a reaction. When a voltage is set between two electrodes, the oxygen with a negative charge in water molecules delivers its electron, resulting in protons, electrons, and oxygen at the anode. In terms of record of success and production capacity, PEM water electrolysis is less advanced, but it offers more room for improvements and cost reduction. PEM technology is being researched at a multi-MW scale and might be utilized for hydrogen energy (distribution services and vehicle) applications (Bessarabov,2018).

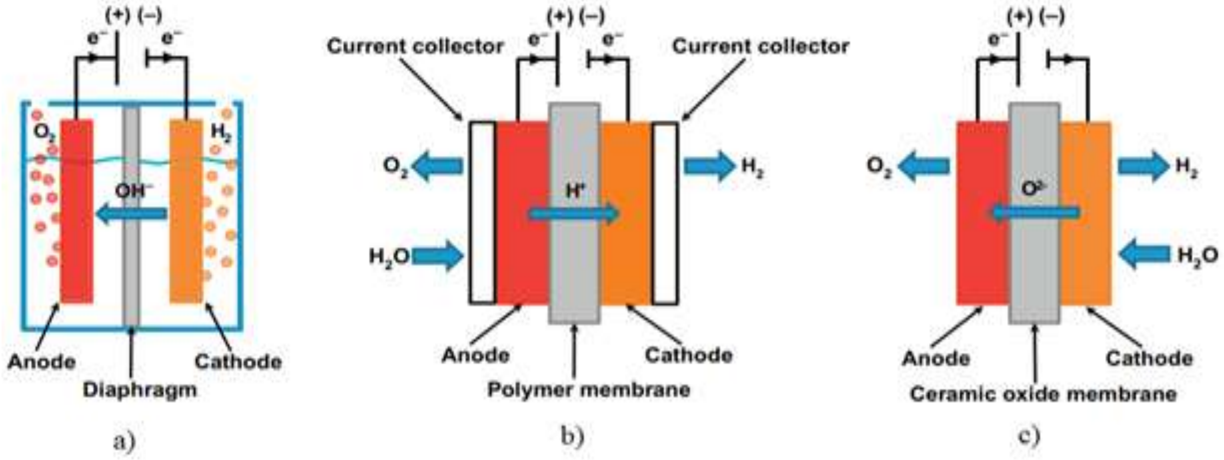

Figure 2. Schematic illustration water electrolysis cell systems, a)Alkaline electrolyzer, b) Polymer-electrolyte membrane electrolyzer, c) Solid oxides electrolyzer (Coutanceau, et al.,2018)

Different Applications of Hydrogen

For decades, the industry has used hydrogen safely in subsequent applications such as petroleum processing and purification (Uchenna & Susu., 2019), glass sanctification, semiconductor production, applications in the aerospace and fertilizer industries(Skorupka& Nosalewicz .,2021), and so on. Moreover, unsaturated fatty acid hydrogenation in vegetable oil is used as a coolant in power plant generators.

One possible application is to replace significant volumes of hydrogen produced by carbon-intensive techniques such as photovoltaics and catalytic converters.Some businesses are currently producing hydrogen-powered semi-trucks and vans for warehousing and distribution operations. Other companies, such as Toyota Mirai and Honda Clarity, are developing hydrogen fuel cell electric automobiles for personal usage. Hydrogen power is also being examined for use in various modes of public transportation, such as buses and trains, as well as fuel cells for boats and submarines (Farrell, et al., 2003; European Commission, 2003). In addition, hydrogen fuel cells have been used in a variety of commercial and military applications. NASA produced some of the first hydrogen fuel cells to power rockets and space shuttles in orbit.

Storage and distribution methods of Hydrogen

The storage and transfer of hydrogen energy are both present and growing concerns. Storage and transportation operations are just as critical as manufacturing procedures. These processes are critical in the hydrogen economy. The goal of storing hydrogen energy is to assemble it safe and efficient to employ anywhere and at any time. Hydrogen has a low volumetric energy density and a high gravimetry energy density in its pure shape (Zhange, et al., 2016). According to National Renewable Energy Laboratory (NREL) research, employing green hydrogen for energy warehouse applications with a duration of 13 hours or longer makes monetary sense—and that's with today's technology (NREL, 2021).

At the moment, hydrogen is delivered via three different methods:

1. Pipeline: This is the most cost-effective method of delivering huge amounts of hydrogen, but its capacity is restricted due to the fact that only around 1,600 miles of pipelines for hydrogen distribution are now available in the United States, according to the American Hydrogen Association. Several of these pipelines are located in close proximity to major petroleum refineries and chemical factories in Illinois, California, and the Gulf Coast.
2. Tube trailers with high pressure: Transporting compressed hydrogen gas in high-pressure tube trailers by truck, railway, ship, or barge is costly, and it is only practical over short lengths of fewer than 200 miles between points.
3. Tankers transporting liquefied hydrogen: Cryogenic liquefaction is a technique in which hydrogen is cooled to a temperature at which it may be converted to a liquid. A cost-effective alternative to high-pressure tube trailers for long-distance transportation of hydrogen by truck, railway, ship, or barge, the liquefaction process is still prohibitively expensive. It boils (or evaporates) from its containment containers if the liquefied hydrogen is not consumed at a sufficiently enough pace when it reaches its consumption threshold. As a result, the rates at which hydrogen is delivered and used must be precisely coordinated (Tashie-Lewis, et al., 2021).

Heating with Hydrogen

In the future of heating, hydrogen is expected to play a significant role. Heating with hydrogen gas and natural gas is being tested in the United Kingdom, where certain places already employ this combination. By 2030, there may be a hydrogen town and maybe a huge hydrogen village in the government's future plans for the next decade (https://fuelcellsworks.com). Replacing natural gas boilers with hydrogen gas boilers may be the simplest way to solve the heating problems. When you burn hydrogen gas, the only product is water. This means that hydrogen gas is a carbon-free fuel source and could be a key method for reducing the amount of carbon in heating and hot water in the world.

The primary advantages of generating hydrogen from offshore wind for house heating are as follows:

a. Hydrogen is a very efficient fuel source (1 kg H = 2.8 kg of natural gas energy). As a result, hydrogen boilers would emit no carbon dioxide (they would exclusively produce steam and heat).
b. Hydrogen might be utilized in place of natural gas in the existing gas grid infrastructure.
c. In comparison to renewable heating solutions, boilers are a typical heating technology for households (heat pumps and solar)(https://eciu.net).

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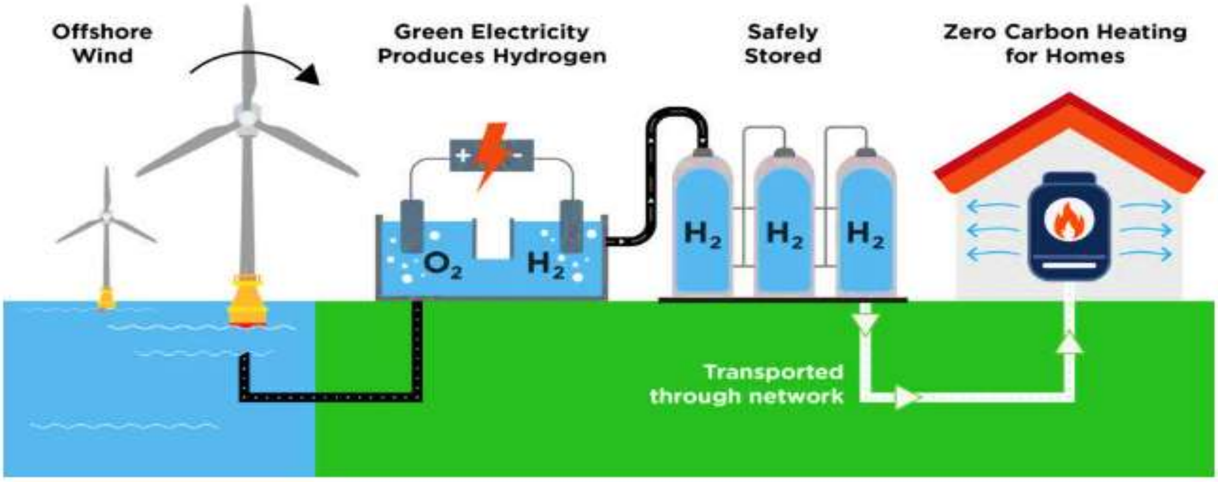

Figure 3. Generation of hydrogen from offshore wind for heating homes (www.boilerguide.co.uk).

The Benefits and Drawbacks of Hydrogen energy

It is possible to store and transmit hydrogen energy, which gives it a significant advantage over competing energy sources. Hydrogen may be used to store excess electricity generated by renewable energy sources like solar panels, wind turbines, and hydroelectric dams. In this manner, energy may be generated and stored on a continual basis (Tarhan & Çil, 2021).

1. Since hydrogen is a renewable energy source, it cannot be depleted, at least not on a human timeline. It is a plentiful supply of energy that surrounds us.
2. No hazardous byproducts are emitted into the atmosphere when hydrogen is burned. Indeed, hydrogen can be turned into drinking water for astronauts once it has been utilized as an energy source.
3. Unlike nuclear energy or natural gas, hydrogen has no adverse effect on human health.
4. Hydrogen is extremely dense in energy and is capable of generating a great deal of power. It is three times more potent than the majority of fossil-based fuel sources, using less hydrogen to do the same activities. This is why hydrogen is employed in space exploration as a fuel source for spacecraft, aeroplanes, boats, automobiles, and fuel cells.
5. To be genuinely carbon neutral, any power needed to produce hydrogen must originate from renewable sources.
6. According to the UK government's hydrogen strategy, off-shore wind power will provide four times more electricity by 2030 than required to meet hydrogen demand.
7. Transitioning to hydrogen would result in the creation of thousands of new jobs. According to the government, switching to hydrogen for household heating will result in the creation of 9,000 jobs by 2030 and 100,000 by 2050. One issue with transitioning to low-carbon heating is that homeowners will bear the cost. However, the three largest boiler manufacturers, Baxi, Ideal Vaillant, and Worcester Bosch, have all committed to maintaining the same pricing for hydrogen-ready boilers as they do for gas boilers.

III. CONCLUSION:

Individual nations' capacity to manufacture hydrogen will eradicate monopolies in the fuel industry, as well as price hikes caused by political situations. Among the numerous energy storage technologies, storing renewable energy in chemicals such as hydrogen can supply considerable advantages such as high energy density, seasonal storage stability, potentially reducing costs of the final products, and the capability to raise renewable power exploitation.

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