IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.301

Volume 3, Issue 1, August 2023

The Hydrogen (Future and Perspective)

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Abstract: Hydrogen, as a versatile and sustainable energy carrier, has garnered significant attention in recent years due to its potential to revolutionize various sectors. This review paper delves into the diverse aspects of hydrogen, encompassing its types and color classification, alongside an exploration of cuttingedge production technologies. The paper further examines the vast range of potential applications for hydrogen, including its role in transportation, refinery processes, ammonia, and methanol production, as well as its overarching significance for the future of energy. Additionally, a comprehensive analysis of hydrogen storage techniques and utilization strategies is presented, shedding light on the challenges and opportunities associated with harnessing hydrogen's potential. Through an in-depth exploration of these facets, this paper provides valuable insights into the evolving landscape of hydrogen utilization and its pivotal role in shaping a sustainable energy future.".

Keywords: Hydrogen , Storage , Decarbonization, Adoption, Sustainable

I. INTRODUCTION

Hydrogen an element that has long held a significant place in the annals of scientific inquiry, is now poised to play a pivotal role in shaping the future of energy and various industrial sectors. Its remarkable properties, including high energy content, environmental friendliness, and versatility, have sparked a renewed interest and enthusiasm for exploring its vast potential as a clean and sustainable energy carrier. In recent years, there has been a surge in research and development efforts aimed at harnessing hydrogen's unique attributes to address the pressing challenges of climate change, energy security, and technological advancement. This paper delves into the future and perspectives of hydrogen, elucidating the evolving landscape of its production, storage, distribution, and applications. By examining the latest developments, breakthroughs, and ongoing initiatives, this research endeavours to provide a comprehensive understanding of how hydrogen is poised to revolutionize various sectors and contribute to a more sustainable and prosperous tomorrow.

1.1 What is Hydrogen?

Hydrogen plays a crucial role as a fundamental resource in the chemical sector. It serves mainly as a reducing agent in activities like oil refining and the production of fertilizers. It is also utilized in the creation of methanol and ammonia, as well as in the elimination of unsaturated double bonds within various molecules, including unsaturated oils and fats. This process is particularly important during the production of hydrogenated vegetable fat or Vanaspati. To truly advance its impact on clean energy practices,[1] Hydrogen, an environmentally friendly energy carrier, is the most abundant element in the universe, constituting 75% of normal matter's mass and over 90% of atoms in quantity. When hydrogen gas undergoes electrochemical oxidation in a fuel cell setup, it produces only pure water as a by-product, releasing no carbon dioxide. Beyond its traditional role as an industrial raw material, hydrogen has gained prominence as a novel energy medium, The utilization of hydrogen is expanding across various sectors such as transportation, electricity generation, and military applications due to its notable benefits of high efficiency and minimal emissions.[2] Obtaining hydrogen in its free form from various sources is essential. Hydrogen possesses remarkable qualities due to its exceptionally low molecular weight, such as high thermal velocity and conductivity, as well as minimal viscosity and density. Notably, it boasts a very low ignition energy and a broad flammability range. These unique attributes, particularly the substantial heat of combustion and the product gases' low molecular weight, establish hydrogen as a preferred choice for rocket propulsion. To enhance convenience in storage, use, and transportation, hydrogen can be transformed into a liquid state. Liquid hydrogen remains colourless and has a liquefaction temperature of 20.3 K. [3]

1.2 Production of Hydrogen

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The production of hydrogen can be classified based on the primary methods used and they are also classified based on colour spectrum which indicates its environmental impact. Based on colour spectrum, they are mentioned below.

- Blue hydrogen: blue hydrogen is an attractive low-carbon alternative, involving hydrogen production from fossil fuels alongside a carbon capture, utilization, and storage (CCUS) system. While utilization is not obligatory for blue hydrogen, it offers a way to significantly reduce carbon emissions. Despite its fossil fuel origin, blue hydrogen boasts lower costs compared to green hydrogen. Blue hydrogen is sometimes described as a low-carbon hydrogen as the steam reforming process does not actually avoid the creation of greenhouse gases.[4]
- Grey Hydrogen: Grey hydrogen refers to hydrogen that is generated through processes such as steam methane reforming, coal gasification, or partial oxidation. Most hydrogen currently produced falls under the category of grey hydrogen. Notably, 40% of this grey hydrogen is a result of secondary chemical processes. Grey hydrogen finds common application in the petrochemical sector and the production of ammonia [4]

  Producing grey hydrogen can be costly due to the energy-intensive method of steam methane reforming. The expense of hydrogen production is also influenced by natural gas prices and the cost of carbon credits, potentially diminishing its competitiveness compared to other fuels or production techniques. Growing interest in cleaner energy has spurred the emergence of alternative hydrogen sources like green hydrogen, generated from renewable energy. These substitutes could gradually rival grey hydrogen in terms of competitiveness.[5]
- Black/Brown Hydrogen: The terms "brown hydrogen" and "black hydrogen" refer to hydrogen produced from lignite (brown) and bituminous (black) coal. This method is considered one of the least environmentally friendly ways of producing hydrogen, as it generates as much CO2 as burning the coal itself would. For each kilogram of brown or black hydrogen produced, approximately 20 kilograms of CO2 are released. Despite its environmental drawbacks, this method is widely used because coal holds the largest global reserves among fossil fuels. Notably, China relies heavily on coal gasification to produce hydrogen, driven by high natural gas costs and abundant coal reserves.[4]
- Yellow hydrogen: yellow hydrogen is generated through electrolysis by utilizing electricity sourced from the energy grid. The amount of carbon emissions produced fluctuates over time, contingent upon the energy sources powering the grid. The grid is formed by integrating electricity from a diverse array of available power sources. These sources and technologies have evolved over the years, with certain options being favoured over others based on the specific country's circumstances.[4]
- Turquoise Hydrogen: Turquoise hydrogen is also derived from methane, but it is generated through a process called methane pyrolysis. Unlike Steam Methane Reforming (SMR), the result of this process includes solid carbon in the form of filamentous carbon or carbon nanotubes. This byproduct has practical applications and can be stored more efficiently, leading to a reduced environmental impact.[4]Methane pyrolysis, which involves breaking down methane into its components, can be categorized into three main processes: thermal decomposition, plasma decomposition (known as the Kvaerner process), and catalytic decomposition. These methods have been recognized and technically implemented for many years. However, the focus on producing hydrogen through thermal decomposition has gained attention only in recent times as the most advanced approach. Despite its long-standing existence, pyrolysis for hydrogen production has not yet become commercially viable.[6]
- purple(violet)& red: pink hydrogen is created by performing water electrolysis with electricity sourced from a nuclear power plant. Similarly, purple hydrogen is produced by combining nuclear power and heat, utilizing both electrolysis and thermochemical water splitting processes. Red hydrogen, on the other hand, is generated by catalytically splitting water at high temperatures, using nuclear thermal power as the energy source. It is worth noting that some viewpoints argue that these forms of hydrogen could be considered equivalent [4]
- Green Hydrogen: Green hydrogen, frequently referred to as "clean hydrogen," "renewable hydrogen," or "lowcarbon hydrogen," is hydrogen generated through water electrolysis, utilizing electricity sourced from renewable energy. The production of green hydrogen, powered by renewable energy, avoids the release of carbon dioxide (CO2) emissions entirely. This form of hydrogen holds significant promise in the shift towards an eco-friendlier energy and transportation framework.[4] Presently, three primary electrolysis methods exist: alkaline water electrolysis (ALK), polymer electrolyte membrane (PEM) electrolysis,

and solid oxide electrolyser cell (SOEC). ALK, the oldest among them dating back to 1920, holds the most advanced stage of development, boasting a substantial 70% market dominance.[6] Alkaline water electrolysis is a method of splitting water using electricity. This process involves two half-cell reactions: the hydrogen evolution reaction (HER) at the cathode and the oxygen evolution reaction (OER) at the anode. During alkaline electrolysis, at the cathode, two moles of alkaline solution are reduced to create one mole of hydrogen (H2) and two moles of hydroxyl ions (OH−). The produced H2 is removed from the cathode, while the remaining hydroxyl ions (OH−) move through a porous separator to the anode under the influence of an electric circuit. At the anode, the hydroxyl ions (OH−) are used to produce half a molecule of oxygen (O2) and one molecule of water (H2O).[7]

II. PRODUCTION TECHNOLOGIES OF HYDROGEN

Hydrogen production technology is a vital aspect of modern research and industry, focusing on methods to generate hydrogen gas for various applications. Hydrogen, a clean and versatile energy carrier, can be produced through processes like steam methane reforming, electrolysis, and biomass gasification. These techniques involve utilizing different feedstocks, such as natural gas, water, or biomass, and applying specific conditions to release and capture hydrogen gas efficiently.

2.1 Steam Methane Reforming

Approximately 96% of the global hydrogen supply originates from fossil fuels, while the remaining 4% is generated through electrolysis. A significant portion of this hydrogen is produced by transforming methane from natural gas through steam conversion or during coal gasification processes.[8]

The main reactions occurring the course of steam reforming of methane are as follows:

$$CH+H_2O\rightarrow\ 3H,\ +\ CO\quad CO+HO\rightarrow\ CO+H$$

$$CH4 + 2H_2O \rightarrow 4H2 + CO_2.$$

The SMR process involves two main steps. In the first stage, natural gas is combined with steam and introduced into a tube-like catalytic reactor. This leads to the production of hydrogen and carbon monoxide. In the second stage, the cooled gas is directed into another catalytic converter along with additional steam. During this step, carbon monoxide gets transformed into carbon dioxide and more hydrogen. Since SMR is a well-established technology, modern systems are quite efficient [10]However, using this method is not an appealing approach for a mature hydrogen economy. The reason is that a significant increase in demand could deplete our limited reserves by a considerable amount. Additionally, the concentration of these gas reserves in a small number of regions globally might lead to geopolitical conflicts and unreliable supplies. Environmental impact is also a significant worry because converting natural gas to hydrogen generates as much pollution and CO2 as directly burning the natural gas. While generating hydrogen from natural gas is a well-established process, producing enough for the world's cars and light trucks could strain the world's conventional methane supply, making natural gas as geopolitically sensitive as oil.[9]

2.2 Gasification of Coal

Gasification is a type of partial oxidation process known as the partial oxidation (POX) process, which is used to produce hydrogen from various hydrocarbon fuels such as coal, heavy residual oils, and low-value refinery products. During this process, the hydrocarbon fuel reacts with oxygen in a ratio that is less than the stoichiometric ratio. As a result, a mixture of carbon monoxide and hydrogen is produced at high temperatures ranging from 1200 to 1350 °C. The primary sources of hydrogen production using gasification include the reforming of natural gas and heavy oil, as well as the gasification of coal, heavy oil, and petroleum coke.[9]Coal gasification is a notably pollutant process, generating double the carbon monoxide emissions compared to hydrogen production based on natural gas. Therefore, if coal gasification is to contribute to lowering emissions in India's energy setup, the implementation of CCUS technology becomes necessary.[10]

2.3 Water Electrolysis

Electrolysis is a method where water molecules are separated into hydrogen and oxygen molecules using electricity and an electrolyser device. There are two main types of electrolysers, alkaline, which employs potassium hydroxide as an electrolyte, and PEM, which uses a solid polymer membrane electrolyte. This process can generate hydrogen by splitting water molecules. Electrolysis can range from a few kW to 2000 kW per electrolyser, producing pure hydrogen and oxygen as by-products. On the other hand, photo-electro-chemical water-splitting is an emissions-free process utilizing solar energy.[9] The Widely usedAlkaline water electrolysis is a method of splitting water using electricity. It involves two separate reactions at the cathode and anode: the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER). In the process, alkaline solution is reduced at the cathode, producing hydrogen (H2) and hydroxyl ions (OH). The generated H2 is released from the cathode, while the remaining OH ions move through a porous separator to the anode under the influence of the electric circuit. At the anode, the OH ions are discharged, resulting in the production of oxygen (O2) and water (H2O).[7] Alkaline electrolysers offer a cost-effective alternative to PEM electrolysis, with reduced capital expenses and a lesser demand for rare materials. Despite their advantages, present alkaline electrolyser technology has a few drawbacks such as restricted operational adaptability, though efforts are underway to enhance this aspect. Additionally, these electrolysers occupy more space and provide lower output pressure. Researchers are actively working on overcoming these limitations through enhanced alkaline technologies, backed by funding for advanced research and development. [10]

A. Photoelectric Water Splitting

Water splitting through photo electrolysis is akin to the process of electrolysis, but it innovatively combines solar energy absorption into a singular unit. This integration serves to enhance the sustainability of our energy sources. In addition to harnessing solar energy, this method also incorporates electricity. Consequently, both photonic and electrical energies collaborate to convert into valuable chemical energy in the form of hydrogen. This groundbreaking technique revolves around absorbing photons possessing energies surpassing the semiconducting photoelectrodes' band gaps. This absorption triggers the creation of electron-hole pairs within photoelectrochemical cells, specifically within semiconductors like TiO2. These electron-hole pairs are then separated through the influence of an electric field, which passes through an electrolyte. The overall effectiveness of this process is influenced by factors such as the photonabsorbing material's nature, surface characteristics, crystalline structure, resistance to corrosion, and overall reactivity.[11]

2.4 H_2 Production from Bio-mass

Biomass conversion methods are categorized into two main types: thermo-chemical and biochemical processes. Thermo-chemical approaches are generally more cost-effective due to their ability to operate at higher temperatures, leading to faster reaction rates. These methods involve either gasification or pyrolysis, where biomass is heated without oxygen to create a gas called "syngas" containing hydrogen and carbon monoxide.[9]

A. Thermo-Chemical Process

Thermochemical methods are highly efficient for generating hydrogen-rich gases from biomass. These techniques primarily include pyrolysis, gasification, and hydrothermal liquefaction. When dried biomass undergoes thermochemical conversion using gasification and pyrolysis, the process resembles that of fossil fuels. Both approaches yield CO and CH4 gases, which can be enhanced for hydrogen production through steam reforming and the water-gas shift reactions. When dealing with moist biomass, the combination of hydrothermal liquefaction and steam reforming is necessary to obtain hydrogen[11]

B. Bio-Chemical process

Due to a growing emphasis on sustainable practices and minimizing waste, there has been a significant rise in research focused on obtaining hydrogen through biological processes. Two main methods for producing hydrogen using biological means are dark fermentative hydrogen production and photo-fermentative processes. In dark fermentative processes, anaerobic bacteria are employed on carbohydrate-rich substances in the absence of light and under oxygendeprived conditions. This results in the production of hydrogen, organic acids, and CO2 from the original biomass. This process operates independently of light, allowing hydrogen to be generated at any time. Biohydrogen production through dark fermentation occurs via biochemical reactions facilitated by enzymes, taking place at regular temperature and pressure levels. Although the amount of hydrogen produced is influenced by factors like substrate type, inoculum, and operational conditions (such as temperature and pH), the potential hydrogen yield is limited by the metabolic pathway of the process.

For instance, while the theoretical maximum yield is 12 mol of hydrogen per glucose molecule, practical limitations in glucose metabolism result in only 4 mol of hydrogen being produced in the acetate dark fermentation pathway. Consequently, various advancements have been documented in scientific literature, including techniques like immobilization and the utilization of additional metal ions and oxide nanoparticles. These approaches aim to enhance hydrogen production to its fullest extent.[11]

III. HYDROGEN STORAGE

Addressing the challenge of hydrogen storage is of utmost importance prior to the development of a hydrogen fuel system that is both technically feasible and economically viable.[9]Hydrogen stands out as a highly promising fuel for the future due to its impressive energy density per unit of mass. It contains 33.33 kWh of energy in every kilogram, which is significantly higher than the energy content of 12 kWh found in petrol and diesel. Nevertheless, it's important to note that storing an equivalent amount of hydrogen would necessitate a greater volume compared to other fuels like petrol and diesel.[12]

3.1 Different Technology of Hydrogen Storage are

A. Compressing storage tank

Here are four categories of pressure vessels suitable for hydrogen storage

- Type 1:These pressure vessels are entirely metallic, typically made from steel or aluminum. They are traditional, cost-effective, and sturdy, weighing around 3.0 lb/L. They can handle pressures up to 50 MPa[13]
- Type 2: These vessels are made of steel and covered with a composite of glass fibers. The structural load is shared between the steel and composite. While Type II costs about 50% more to manufacture than Type I, it is 30-40% lighter and has the highest[13]
- Type 3: These vessels feature a full composite wrap with a metal liner, mainly for sealing (aluminum). The load is mostly borne by the carbon fiber composite structure. They have been reliable up to 45 MPa, but face challenges in passing aging tests at 70 MPa. Type III offers a weight of 0.75-1 lb/L, half of Type II, but is twice the cost[13]
- Type 4: Fully composite vessels, usually lined with materials like High Density Polyethylene (HDPE) and reinforced with carbon fiber or carbon-glass composites for structural strength. Although Type IV is the lightest option, it remains relatively expensive. These vessels can withstand pressures up to 100 MPa.[13] Hydrogen transportation via pipelines and tube trailers often relies on compressed hydrogen storage. Yet, the weight of gas cylinders limits transport efficiency. Researchers are developing lighter materials for high-pressure hydrogen compression. Addressing heat transfer during compression is another challenge, as rising temperatures can lead to composite degradation. To tackle this, studies focus on enhancing heat transfer through high thermal conductivity materials and improved structural designs[12]

B. Underground Hydrogen Storage

Various solutions have been suggested for large-scale hydrogen storage, aside from burying tanks and compressing hydrogen into gas or liquid. Hydrogen storage options like aquifers, depleted natural gas and oil deposits, and salt caverns are the primary choices for storing hydrogen on a larger scale in the medium and long term. The first two types have a porous structure, and their storage capacity might be influenced by geological conditions. Globally, around 75% of underground hydrogen storage occurs in depleted deposits. Recently, there has been significant interest in using salt caverns for hydrogen storage due to their stable and impermeable salt cavern walls. Salt caverns can vary in volume, ranging from 100,000 to 1,000,000 cubic meters,operating at a maximum pressure of 200 bar. However, the advancement of salt cavern hydrogen storage is constrained by certain technical factors, such as the integrity of boreholes and the transfer capacity of surface installations. Additionally, considerations related to the environment, sustainable development, and location planning are crucial aspects to address.[12]

C. Liquid or Cryogenic Hydrogen Storage

Liquid hydrogen offers a compact storage solution by converting hydrogen into a liquid state at extremely cold temperatures around 20-21 K and normal pressure. This transformation yields a volumetric density of approximately 70.8 kg/m³, slightly surpassing the density of solid hydrogen at 70.6 kg/m³. Nevertheless, the process of liquefying hydrogen is both time-consuming and energy-intensive, leading to a loss of about 40% of the energy during this conversion. Currently, liquid hydrogen finds application in specialized high-tech contexts such as space exploration, but its widespread commercial adoption has yet to be realized.[12]

An extra safety layer, like a vacuum jacket, is added to provide further protection in case of accidents involving hydrogen. Hydrogen has limited expansion energy at cryogenic temperatures, which means that even if there's a leakage or tanker rupture, a severe explosion is unlikely unless there's an ignition source. The extremely low temperature of leaked hydrogen gas can potentially cause harm and disrupt the functioning of nearby valves and pressure relief devices that aren't designed to handle such conditions. An incident resembling this scenario occurred in 2016 in a cryogenic hydrogen laboratory, where a pressure relief valve failed to operate as intended because it was located in a section not expected to experience such cold temperatures, leading to unintended consequences.[13]

D. Matarial Based H_2 Storage, Chemical sorption Chemical sorption

Chemical sorption involves splitting hydrogen molecules into atoms, incorporating them into a material's structure. Metal hydrides are renowned for this purpose.Reducing costs, weight, and operating temperature, improving chargedischarge kinetics, and managing unwanted gas formation during desorption are key challenges. While the focus was on solid materials, Liquid Organic Hydrogen Carriers (LOHCs) are promising. LOHC systems chemically bond hydrogen with hydrogen-lean molecules, releasing it through catalytic dehydrogenation.[13]Porous material-based storage systems offer a promising avenue for achieving high-capacity and dependable storage solutions. Among the various porous materials, Metal Organic Frameworks (MOFs) and porous carbon materials stand out as particularly promising. This approach presents advantages such as large surface area, minimal hydrogen binding energy, quicker charging and discharging kinetics, and cost-effectiveness in terms of materials. Furthermore, the potential for physical absorption could address thermal management concerns during the storage unit's charging and discharging processes. Nevertheless, there are certain challenges associated with this approach. These include the weight of the carrier materials, the necessity for low temperatures and high pressures, and the current limitations in gravimetric and volumetric hydrogen density[12]

IV. FUEL CELL TECHNOLOGY

A fuel cell is an electric cell designed to receive a continuous supply of fuel, unlike storage cells. This allows it to consistently generate electrical power over an extended period. These cells transform hydrogen or hydrogen-rich fuels directly into both electrical energy and heat through an electrochemical reaction involving hydrogen and oxygen, resulting in the formation of water. This process is essentially the reverse of electrolysis. Because the conversion of hydrogen and oxygen gases into water happens electrochemically, fuel cells offer numerous advantages over heat engines. These benefits encompass high efficiency, nearly silent operation, and, in the case of hydrogen as the fuel, the absence of pollutant emissions. Furthermore, if the hydrogen used is derived from renewable energy sources, the electricity generated can be truly sustainable.[14]

Typically, fuel cells consist of three key components: the anode, cathode, and electrolyte. Among these, the most crucial component is the electrolyte. The choice of electrolyte determines the properties, behavior, and functioning of the fuel cell. Therefore, the type of electrolyte employed essentially defines the kind of fuel that can be utilized. Regardless of the specific type of fuel cell in use, their operational principle remains consistent.[15]

4.1 Classification of fuel cell

Fuel cells are categorized by the electrolyte type they utilize during operation. This categorization is based on the chemical traits of the specific fuel cell. The specific electrochemical reactions taking place within the cell determine its classification. Factors such as the fuel needed also influence the electrolyte choice, which in turn determines the chemical

ISSN 2581-9429 IJARSCT

reaction occurring in the process. Additionally, these mentioned characteristics significantly impact the potential applications of the fuel cell. Certain types of fuel cells are designed with specific uses in mind.[15]

- Proton Exchange membrane fuel cell : PEM fuel cells utilize a solid polymer film as an electrolyte, conducting hydrogen ions (H+) from anode to cathode. This film comprises acidified Teflon. These fuel cells usually work at 70 to 90 degrees Celsius (160 to 195 degrees Fahrenheit) and 1 to 2 barg (15 to 30 psig) pressure. Each cell can generate around 1.1 volts DC.[16]
- Phosphoric acid fuel cell: Phosphoric acid fuel cells employ an electrolyte that facilitates the movement of hydrogen ions (H+) from the anode to the cathode. This electrolyte, comprised of liquid phosphoric acid contained within a matrix of silicon carbide material, is responsible for this ion conduction process. These specific fuel cells operate effectively within a temperature range of approximately 300 to 400 degrees Fahrenheit (150 to 205 degrees Celsius) and under a pressure of around 15 pounds per square inch gauge (1 bar absolute). Notably, each individual cell can generate an electrical output of up to approximately 1.1 volts DC.[16]
- Molten carbonate fuel cell: Molten carbonate fuel cells utilize an electrolyte that conducts carbonate ions (CO3) from the cathode to the anode, a unique approach compared to other fuel cell types that transport hydrogen ions from anode to cathode. The electrolyte consists of a molten blend of lithium and potassium carbonates, held in place by capillary forces within a ceramic support structure made of lithium aluminate. This setup forms a thick paste at the fuel cell's operational temperature, effectively sealing gases at the cell's edges. These fuel cells function at around 1200°F (650°C) and 15 to 150 psig (1 to 10 barg) pressure, yielding an output of approximately 0.7 to 1.0 VDC per cell.[16]
- Solid oxide fuel cell: Solid oxide fuel cells utilize a ceramic electrolyte that conducts oxide (O) ions from the cathode to the anode, which is unlike most other fuel cell types that transport hydrogen ions from the anode to the cathode. The electrolyte is typically made from solid oxide, often zirconia, stabilized with additional rare earth element oxides like yttrium. These fuel cells work at around 1830°F (1000°C) and a pressure of 15 psig (1 barg), and each cell can generate between 0.8 and 1.0 volts of direct current.[16]
- Alkaline fuel cell: Alkaline fuel cells utilize an electrolyte that conducts hydroxyl (OH–) ions, transporting them from the cathode to the anode. This is in contrast to various other fuel cell types that convey hydrogen ions from the anode to the cathode. The electrolyte usually consists of a molten alkaline blend like potassium hydroxide (KOH), which can either be mobile or stationary.Alkaline fuel cells function within a temperature range of approximately 150 to 430°F (65 to 220°C) and operate at a pressure of around 15 pounds per square inch gauge (1 bar absolute). Each individual cell is capable of generating voltage between 1.1 and 1.2 volts direct current (VDC).[16]

4.2 Potential Application of fuel cell

- Immobile Power: Fuel cells have gained significant traction in power generation due to their enhanced efficiency. Both low and high-temperature fuel cells offer promising potential for utilization in this domain. Variants such as PEM, SOFC, and PAFC are typically employed in small power systems. Low and hightemperature fuel cells each have their distinct areas of applicability. Notably, low-temperature fuel cells offer the advantage of quicker start-up times. For stationary applications, an operational duration of 40,000 hours is required, but the challenge lies in managing the start-up time. High-temperature fuel cells like SOFC and MCFC can be directly integrated into heat cycles or combined systems, providing further options for their implementation.[15]
- Transportation: In the modern era, transportation plays a crucial role, yet many existing technologies have proven to be environmentally unsustainable. As a result, there's a pressing need to adopt new technologies.

  Researchers have identified the potential of PEMFC technology in revolutionizing vehicles. This technology offers distinct advantages, including a lower operating temperature range. These attributes make PEMFCs particularly suitable for various modes of transportation. One remarkable aspect is that these technologies don't necessarily rely on pure hydrogen as fuel and can operate without intricate moving parts. Additionally, they are less susceptible to significant performance degradation. Promising outcomes have been witnessed in companies such as BMW and Delphi automotive systems. They have successfully developed

SOFCs as auxiliary power sources and have begun incorporating PEM fuel cells to replace traditional hydrogen combustion engines. Notably, this technology has already been successfully implemented in the BMW 7 Series, marking a significant step forward.[15]

- Potable device: Fuel cells are set to find extensive use in various devices like laptops, smartphones, and telephones, with their applications extending notably to the military sector. This domain will also encompass the aspect of sustainability in terms of growth and development.[15]
- Space application: Space applications have demonstrated the effectiveness of this technology as a reliable source of conventional energy. It has the ability to generate a continuous electrical output of 1.5 kilowatts, as proven during the Apollo missions. The robust alkaline fuel cells exhibited remarkable dependability, with the fuel cell capable of providing nearly 12 kilowatts of consistent power over extended periods and 16 kilowatts for shorter durations. The shuttle program itself stands out for its exceptional reliability. Moreover, in space, this technology not only supplied electrical energy but also served astronauts for drinking purposes.[15]

V. FUTURE OF GREEN HYDROGEN IN INDIA

Hydrogen possesses advantageous qualities and widespread availability that position it as a promising fuel for the future compared to other alternatives. It stands out as a clean energy source, boasting a considerable energy concentration, and is adaptable for use in internal combustion engines and fuel cells. When employed in fuel cells, only steam is emitted in the form of water vapor, while in internal combustion engines, the primary emission is nitrous oxide (NOx). Additionally, hydrogen's lightweight nature and non-toxic attributes further contribute to its appeal as a viable fuel option.[14]India's strong dedication to ambitious Climate Goals has gained widespread recognition internationally. Our accomplishments have aligned with our ambitious targets. India currently leads in terms of the fastest expansion of Renewable Energy capacity globally. Additionally, India has positioned itself as a highly appealing location for investments in Renewable Energy projects. With a clear objective to attain energy self-sufficiency by 2047 and to reach Net Zero emissions by 2070, India's focus remains on track towards a sustainable energy future.[17]

5.1 Green Hydrogen Mission of INDIA

The primary goal of this initiative is to establish India as a global hub for producing, utilizing, and exporting Green Hydrogen and its byproducts. This aligns with India's aim to achieve self-reliance through clean energy, setting an example for the global shift towards clean energy sources. The mission will have substantial positive effects, including a significant reduction in carbon emissions within the economy, decreased reliance on imported fossil fuels, and positioning India as a leader in Green Hydrogen technology and markets.To realize these objectives, the initiative plans to develop the capacity to produce a minimum of 5 million metric tons of Green Hydrogen annually by 2030, with the potential to increase to 10 million metric tons per year as export markets grow. The mission will actively promote the replacement of fossil fuels and their derivatives with renewable alternatives based on Green Hydrogen. This encompasses the substitution of fossil fuel-derived Hydrogen with Green Hydrogen in processes like ammonia production and petroleum refining. It also includes incorporating Green Hydrogen into City Gas Distribution systems, employing it in steel production, and utilizing Green Hydrogen-derived synthetic fuels (such as Green Ammonia and Green Methanol) to replace conventional fuels in various sectors, including transportation, shipping, and aviation. Furthermore, the mission's ambition extends to positioning India as a frontrunner in the technology and manufacturing of key components like electrolysers and other technologies essential for Green Hydrogen production.[17]

5.2 Potential role of hydrogen in India

The potential role of hydrogen in India holds a Potential Application of hydrogen in various sector such as Following.

- Transportation: he transportation sector is responsible for 17% of India's overall energy consumption. In this sector, oil products hold the primary position as the most widely used fuel, making up 47% of India's oil product consumption. India's reliance on imports covers 85% of its crude oil needs, which has a substantial negative impact on its balance of payments according to the IEA in 2020. The emissions from the transportation sector also play a significant role in local air pollution, contributing to India's air quality issues. Simultaneously, the lack of accessible and affordable public transportation options, along with the high expenses associated with private modes of transport, hampers the availability of convenient and reasonably priced transport services. The major application of hydrogen in transportation are seen in Buses, Truck, shipping and in Aviation.[10]
- Industry: Right now, both in India and around the world, the industry sector relies heavily on hydrogen. Most of the hydrogen is currently put to use in four main areas: fertilizers, refineries, petrochemicals, and methanol production. In India specifically, a large portion of methanol is imported, which means that the main areas where hydrogen is used are fertilizers and refineries, each contributing about half of the demand. As India's population and needs increase, these sectors are expected to grow further, requiring more hydrogen. It's crucial for these industries to prioritize obtaining hydrogen from low-carbon sources whenever possible to meet this new demand in an environmentally friendly way. In industry the potential sector are Fertilizer industry, Methanol Production industry, Refinery, and Iron steel industry
- Fertilizer industry: In India, the fertilizer industry heavily relies on fossil fuels, primarily natural gas. This natural gas is utilized to create ammonia, which serves as a crucial element for supplying nitrogen in various fertilizers that contain nitrogen. This ammonia can either be directly used for its nitrogen content or incorporated into more intricate fertilizers that offer additional nutrients alongside nitrogen. The use of fertilizers is predicted to rise from approximately 45 kg per person at present to about 75 kg per person by 2050. According to the IEA's calculations, the demand for fertilizers levels off at roughly 85–135 kg per person (as of IEA's 2018 data). It's important to highlight that there's a considerable level of uncertainty regarding future fertilizer demand, especially considering the influence of policies promoting zero-budget" natural farming practices.

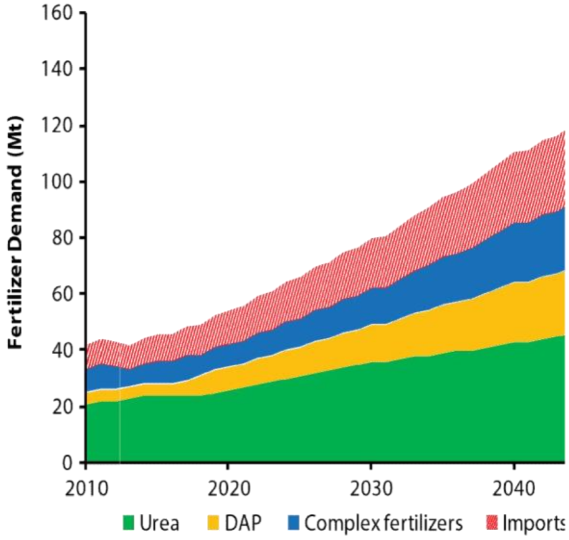

Fig: : Demand for fertilizers – domestic production and import, 2010–2050 (Source: (Ministry of Chemicals and Fertilizers, 2020) (FAI, 2020)

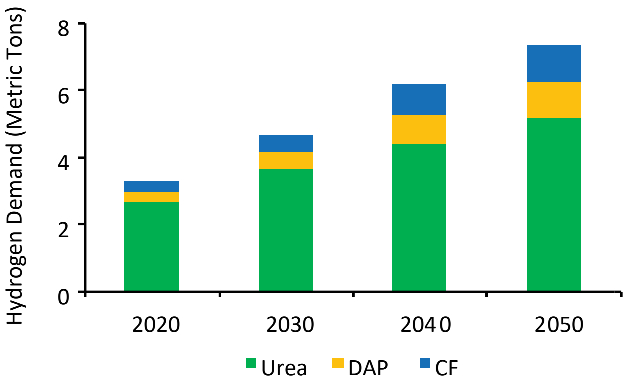

Figure : Hydrogen demand in the fertilizer sector, 2020–2050

Source: TERI analysis based on (FAI, 2020)

It is clear that demand for fertilizer products will increase rapidly out to the mid-century but to understand hydrogen requirements for India, it would require us to also project the share of this demand that will be met by domestic production. India currently imports 25–30% of fertilizers but we assume this would continue to fall steadily over time. Based on expert inputs, we assume that the share of urea falls over time, being replaced by DAP and other complex fertilizers. it Estimated that till 2050 The demand of hydrogen become 7.5(Mt)

Methanol: Currently, the methanol industry in India is relatively small, with a demand of approximately 2 million tons from other industrial users who require it for chemical production. However, this demand is projected to grow rapidly, while a significant portion of methanol will continue to be imported. This trend is mainly due to a substantial amount of methanol being produced from natural gas, which is abundant and available at very low costs in the Middle East. China also contributes significant methanol quantities, largely sourced from coal and coke oven gas. The Middle East's methanol production relies on natural gas with an average price of around $2–3 per million British thermal units (mmbtu), in stark contrast to India's imported natural gas price of approximately $10/mmbtu. Because of this significant price difference, large-scale domestic methanol production using natural gas isn't economically feasible.Anticipated policy backing from the Indian government is set to propel a swift growth in methanol demand in the upcoming years. This growth is projected to be substantial, increasing about five times from current levels to 2050.

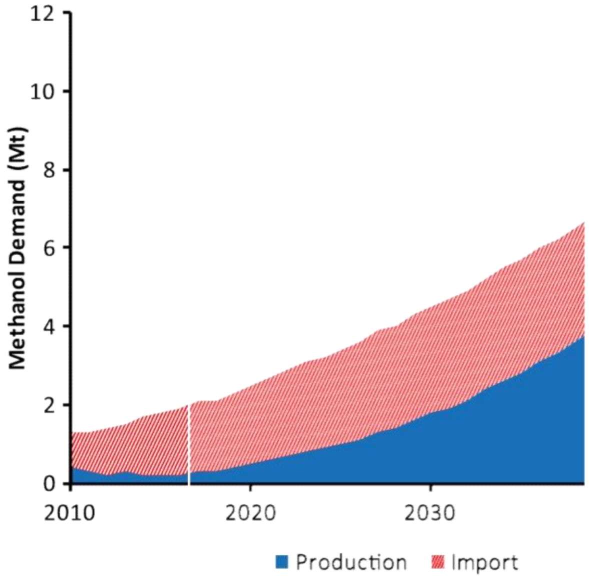

Fig: Methanol demand – domestic production and import, 2020–2050 Source: TERI analysis based on (Ministry of Chemicals and Fertilizers, 2019)

The primary driving force behind this surge will be the ongoing utilization of methanol within the chemical industry. Additionally, there's an expectation that the current import dominance, constituting 80% of the supply, will reverse significantly by 2050, dropping to just 20%. This shift will be propelled by supportive policies and a clear objective to reduce the nation's energy imports. By the year 2050, the quantity of hydrogen needed for methanol production will be slightly over 1 million tons, significantly less compared to the demand observed in the fertilizer sector. This discrepancy arises from the fact that the overall need for methanol is lower in comparison to fertilizers, and the amount of hydrogen required per unit of methanol is also lower when compared to ammonia.[10]

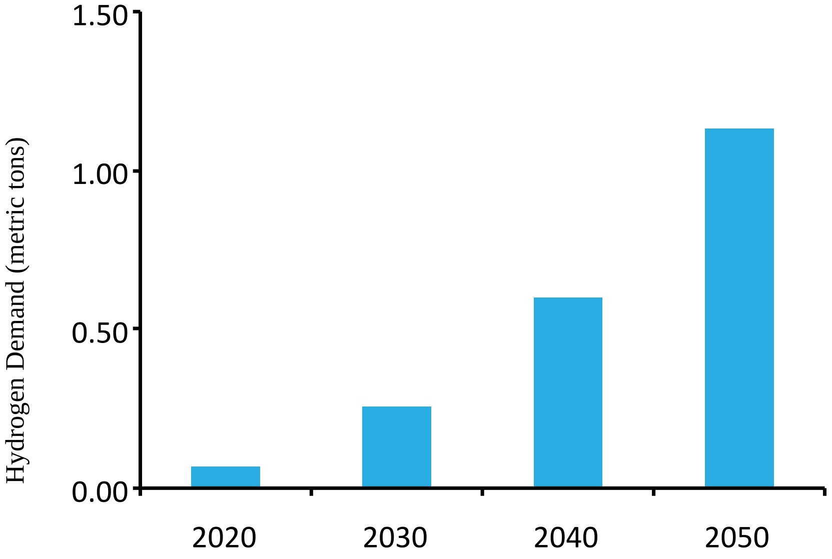

Fig: Hydrogen demand for methanol, 2020–2050

Source: TERI analysis

Currently, India's refinery industry plays a significant role in processing a substantial volume of crude oil, primarily utilized in both transportation and industrial sectors. About 30% of the country's primary energy demand relies on crude oil, with more than 80% of it being imported. Hydrogen serves a crucial role in refining crude oil and conducting desulphurisation. Different refined products adhere to varying sulphur content regulations and industry prerequisites. A higher requirement for low sulphur content drives the demand for hydrogen. Policies like the BSVI Standards, aiming for reduced sulphur in transportation fuels, contribute to an increased need for hydrogen in this domain. While refineries produce some hydrogen as a by-product during their refining processes, this by-product is often inadequate to meet the overall hydrogen demand. Consequently, additional on-site hydrogen production becomes essential, usually through natural gas or naphtha reforming. These reforming units are constructed on-site to satisfy the hydrogen needs of the refinery throughout its operational lifespan. India presently boasts a refining capacity of 254 million tonsper annum (Mtpa), ranking fourth globally behind the United States, China, and Russia. The refining capacity and complexity are on the rise to accommodate the heightened demand for petroleum products. This strategic growth helps reduce imports of refined goods, thereby boosting India's value addition within the sector. By 2030, the country aims to double its refining capacity to approximately 500 Mtpa. Based on our analysis, we've made certain growth assumptions for the production of green hydrogen within the refinery sector. In the Baseline scenario, we anticipate a gradual displacement of natural gas-based hydrogen by green hydrogen, commencing around 2030 and reaching a share of approximately 30% by 2050. In the Low Carbon scenario, we envision an earlier adoption of green hydrogen in the refinery sector, starting in 2025. This acceleration is attributed to quicker reductions in costs and more robust policy support, possibly including emissions penalties or green subsidies. With these interventions, green hydrogen has the potential to cater to about 50% of the refinery industry's needs by 2050.

At present, India holds the position of the world's second-largest steel producer and third-largest consumer of steel. The Indian steel industry exhibits a higher degree of diversity compared to many other nations, encompassing a wide array of differently sized facilities in both primary and secondary steelmaking domains. Diverse technologies are also in use, including the Blast Furnace – Basic Oxygen Furnace (BF-BOF), coal-based Direct Reduction (DR), gas-based DR, Electric Induction Furnace (EIF), and Electric Arc Furnace (EAF).

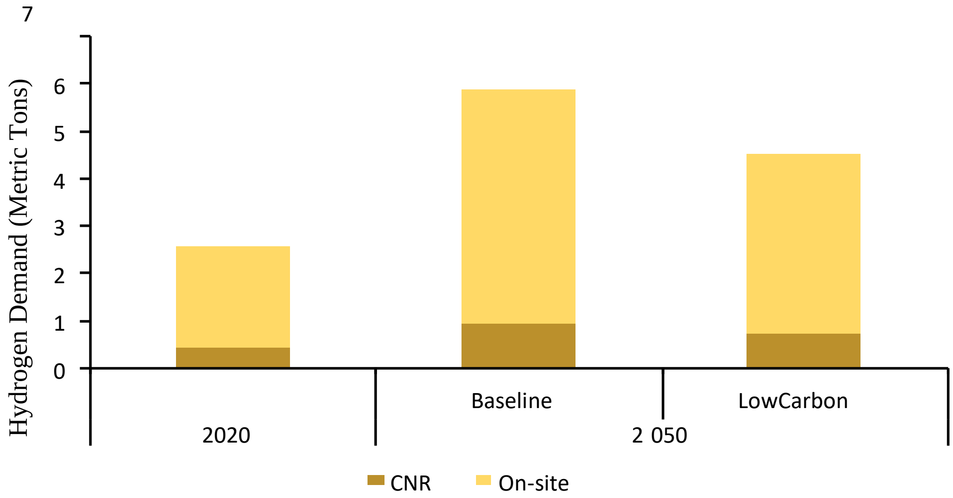

Fig: Hydrogen demand in refineries, 2020 and 2050

Source: TERI analysis based on interactions with the IEA

The coal-based DR method, in particular, is unique to India's steel sector, effectively addressing local steel needs with competitive costs against larger integrated steel plants. This reliance on the technology stems from India's abundant domestic coal reserves, coupled with the limited availability of suitable domestic natural gas and high-quality coking coal.As demand for steel slows in developed parts of the world, the majority of new steel demand is projected to emerge from rapidly industrializing nations in South Asia and Africa. India, in particular, will play a significant role in this surge of steel demand, necessitating fresh primary steelmaking capacity. Concurrently, ambitious policies focusing on scrap steel utilization will foster growth in secondary steelmaking. The imperative for the steel industry lies in adopting low-emission primary steelmaking technologies to achieve near-zero emissions levels by the mid-century or 2060.Based on the preceding analysis, we envision a minor role for hydrogen direct reduction in the Baseline scenario, where policy support is limited. As the costs of green hydrogen decline, we anticipate the construction of hydrogen direct reduction plants to commence around 2040, with gradual progress in implementation. Given the favorable cost of coal, both smelting reduction and coal-based direct reduction facilities are expected to remain competitive, thereby constraining the extent of hydrogenutilization.

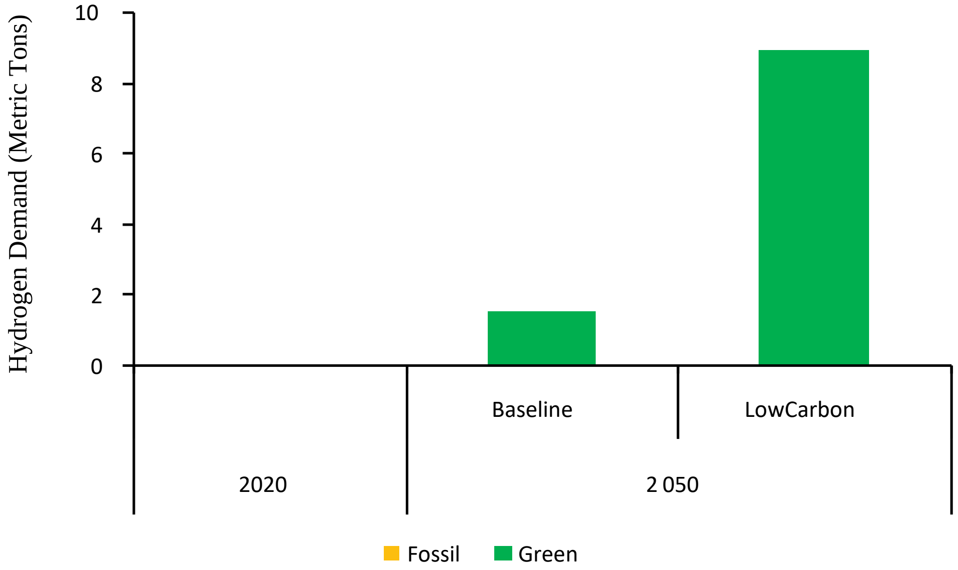

Fig: : Hydrogen demand for the steel sector in the Baseline and Low Carbon scenarios Source: TERI analysis

In the context of the Low Carbon scenario, characterized by robust policies to expedite the adoption of hydrogen direct reduction facilities, the demand for green hydrogen is projected to surge from 2030. This rapid growth continues until 2050, becoming the primary driver behind nearly all new primary capacity expansions during the 2030-2050 period. Consequently, by 2050, approximately 50% of primary capacity is anticipated to rely on hydrogen direct reduction, necessitating an annual supply of around 9 million tons of green hydrogen. This sector emerges as the most significant hydrogen demand contributor by 2050, underscoring the energy-intensive nature of steel production and the potential role that hydrogen could assume in curbing emissions within this sector, particularly with appropriate policy backing.[10]

VI. CONCLUSION

In summary, this review paper has delved into the vast possibilities that hydrogen offers as a future energy source. With its potential to revolutionize multiple sectors, from energy storage to transportation and beyond, hydrogen stands as a key contender in the pursuit of sustainable and eco-friendly solutions. As our understanding of its applications continues to expand and technology advances, it is evident that hydrogen has the capacity to reshape the energy landscape. By capitalizing on its unique properties and fostering further research, we pave the way for a future where hydrogen takes center stage in meeting the global energy demand while minimizing environmental impact. And different type of hydrogen According to their environmental. and different production technologies.

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