Innovations

Hydrogen as an Energy Carrier: Challenges and Solutions in Production and Storage Physics

Mr. Hemant K Suryawanshi[1], Mr. Dilip D. Thorat[1], Mr. Atul P Naikwade[2], Dr. Surendra M. Yenorkar[3]

Abstract: *Hydrogen is one of the crucial energy source for the global transformation to a sustainable decarbonized energy system. Due to its versatile and high-energy-density nature hydrogen enables decarbonization in industries like power generation, transportation and heavy manufacturing. Some challenges in hydrogen productionto overcome this issue researcherfocused on electrolysis of water, thermochemical processes, challenges with high-temperature processes and their environmental impacts and use of renewable energy sources such as solar and wind energy production. challenges in hydrogen storage system to overcome these challenges, need innovations in electrolysis, use of advanced materials like pervoskites, novel storage approaches such as use of liquid organic hydrogen carriers (LOHCs), advanced storage options comprise compressed hydrogen, cryogenic liquefaction, and metal hydrides and new adsorbents like MOFs.This article gives an importance of hydrogen, application of hydrogen as energy carrier in varies sectors like transportation, electric buses, vehicles, industrial decarbonization. In Future role of hydrogen promise useful energy carrier, clean and essential for global transition to sustainable energy source. To overcome these challenges researchers focusing to development of energy efficient electrolysis system, hybrid electrolysis system for hydrogen production, development of safer and scalable storage technology. Overcoming these hurdles will let hydrogen contribute importantly in this journey toward a resilient and sustainable energy future.*

Keywords: *Hydrogen, Energy Storage, Productions, Challenges and Applications.*

1.0 Introduction

1.1 Hydrogen's Role in a Decarbonized Energy Landscape

Hydrogen playimportantrole for achieving a decarbonized energy system, as one of the crucial energy carrier globally. hydrogen has the potential to transformdecarbonize sectors that include transport, industrial processes. Hydrogen-powered fuel cell cars as a cleansubstitute in comparison with internal combustion engines while using only water as its by-product; Bhandari et al., 2022 [1]. Also, hydrogen can replace fossil fuels in steel &industrial production, in which hydrogen works as a reducing agent instead of carbon and givessignificantly to the decrease of GHG emissions(*IEA, 2021*) [2]. Hydrogen has the ability for storing energy and releasing it when needed, offering significant synergies with renewable sources, wind, and solar power-the source that makes up their intermittency and allows for grid stability(*Zhang et al., 2020*) [3].

1.2 Physics of Hydrogen as an Energy Carrier

The physics of hydrogen reinforces not only its promise but also major difficulties associated with its uses as an energy carrier: while hydrogen bears really high gravimetric energy density of about 33.3 kWh/kg—pretty much the highest for energy carriers when judged based on weight—it is weak from the perspective of its volumetric density at low temperature and pressure conditions compared to any other form of hydrocarbon fuel (Züttel, 2003) [4]. That property puts this fuel immediately into several highly specific niches like flying and heavy transport—hardly can one imagine hydrogen applicable, at least in nearest prospective, for other widely spread consumption directions. However, the volumetric energy density is small enough to impose difficult conditions from a storage and transport viewpoint. Hydrogen, consisting of the lightest molecule with a molecular weight of merely 2 g/mol, calls for very advanced levels of compression or liquefaction techniques in order to realize practical values of energy density in lots of applications (Bossel et al., 2003) [5].The production of hydrogen is also controlled by physical and thermodynamic incompetence. For instance, for hydrogen production water electrolysis is a commonly used method overcoming significant activation barriers, with efficiency restrictions executed by the thermodynamics of the hydrogen evolution reaction (HER) (*Matsumoto & Sato, 2017*) [6]. Likewise, storage solutions such as compressed liquid and hydrogen gas are delayed by energy dead and composite engineering desires to handle high pressures or cryogenic temperatures (*Kumar et al., 2021*) [7].

2.0 Challenges in Hydrogen Production

Hydrogen production is the most important step in making use of it as an energy carrier. The production processes are characterized by complex physical and chemical phenomena with great challenges regarding efficiency, cost, and environmental impact. Use of hydrogen as energy carrier is essential step to discover one of energy carrier but it has challenges in production of hydrogen with high efficiency, its environmental impacts and cost. Main methods include water electrolysis, thermochemical processes, and, under development, photocatalytic and biological approaches. Each of these methods presents particular challenges rooted in the physics and chemistry of hydrogen generation.

2.1 Electrolysis of Water

Water electrolysis is the mainstay of hydrogen production in general and the green hydrogen pathways incorporating renewable electricity in particular. In this process, water molecules are split into hydrogen and oxygen using electrical energy.

Physics of splitting of water molecule:

This reaction, while involving the surmounting of a thermodynamic energy barrier of 1.23 V at standard conditions, practically requires voltages in the range of 1.6-2.0 V because of kinetic losses and over potentials at both the anode and cathode. activation barriers in hydrogen and oxygen evolution reaction are control inefficiencies, both reactions are strong dependence on surface properties and electrode material. (*Zeng & Zhang, 2010*) [8]

Thermodynamic and Catalyst Performance Efficiency Limits:

The thermodynamic effectiveness is significantly restricted by energy losses related to irreversible reactions and heat dissipations in water electrolysis process. The current state-of-the-art electrolyzers, including both PEM and alkaline electrolyzers, are able to reach efficiencies of around 65-75% (Wang et al., 2021) [9]. The research carried out recently has been focused mainly on the optimization of catalyst performance by the use of nanostructured material examples, which are typically IrO_2 or RuO_2 for OER and platinum-based catalysts for HER, these material improve reaction kinetics but it is costly,Wei et al. (2020) [10].

2.2 Thermochemical Processes

Partial oxidation and SMR involves in thermochemical method, leading hydrogen production in industries it has some disadvantages.

Difficulties of the High-Temperature Process:

In SMR, methane is decomposed into hydrogen and carbon monoxide at a very high temperature, in the range of 700-1,000°C. Such high temperatures require energy-intensive operations at very high costs with ensuing low efficiency. According to Smith et al. (2019) [11].

Environmental Impacts and Carbon Capture Integration:

SMR is a carbon-intensive process; more than 10 kilograms of CO_2 are emitted it produce for one kilogram of hydrogen. To reduce the emission CCS technology is used, mixing improves the effective barrier and production cost. Currently, CCS system capture 60-90% of emissions(IEA, 2020).

2.3 Photocatalytic and Biological Methods

Capturing renewable energy for sustainable hydrogen production, modern techniques such as biological and photocatalytic water splitting method used.

Photon Absorption and Charge Transport Physics Role

Photocatalysis is a process that applies semiconductor photocatalysts, including the likes of TiO_2 and CdS, to absorb photons to result in electron-hole pairs. Thereafter, the generated charge transports to the surface for appropriate redox reactions with very high efficiency, normally having a huge influence on the rate of water splitting as reported by Chen et al. (2019) [12].

Limitations in Quantum Efficiencies:

Less than 10% quantum efficiencies recognize most of the photocatalysts which has large gap between theoretical limits (Fujishima & Honda, 1972) [13]. To increase charge separation and application heterojunctions have been developed but still need to extra optimization for large applications (Wang et al., 2020) [14].

2.4 Recent Advances

1. **Improvement in Efficiency of Electrolysis:**
   Wei et al. (2020) [10] proved that iridium-nickel hybrid catalysts decrease the overpotential of the OER, raising the efficiency of PEM electrolyzers as high as 80%. This is a huge step toward making green hydrogen viable economically.

2. **Low-Carbon SMR:**
   Novel device discoveredsystems with integrated CCS that release up to 95% of CO_2 emissions, thus reducing the carbon footprint of hydrogen fabrication Smith et al. (2019) [11].

3. **Improved Photocatalysts:**
   Mesoporous TiO_2-CdS composite photocatalyst reported 15% of quantum efficiency signifying the highest value obtained over visible light by water splitting system, Chen et al. (2019) [12]. Indeed, this represents a high improvement in the development pathway toward sustainable hydrogen production.

4. **Biological Innovations:**
   Wang et al. (2020) [14] have pointed out that the introduction of biohydrogen-producing genetically engineered algae increased 1.5 times compared to the wild strain.

3.0 Challenges and Solutions in Production and Storage

Decarbonization of several sectors such as, transportation, electricity production, industrial processes, hydrogen is one of the favorable energy carriers due to their high energy content. Hydrogen faces huge barriers to practical storage and transport due to extremely low volumetric energy densities while it is in a gaseous or liquid state.In this paper, the main physics challenges for hydrogen storage are reviewed; the main emphasis is placed on three methods of storage: compressed hydrogen gas, liquid hydrogen, and solid-state storage. Each of these options faces specific problems that will be analyzed in detail, along with current solutions and research directions for overcoming such barriers.

3.1 Compressed Hydrogen Gas

Due to straightforward approach and recognized technology compressed hydrogen storage method is commonly used. In this method to improve volumetric energy density, compressing hydrogen gas pressure between 350 and 700 bar. Still numerous limitations and challenges arises.

Physics of Compression and Limitations of Current Technologies:

According to ideal gas law, for compressing hydrogen, decrease the volume as a result increase in pressure. For this process continuous thermodynamics work required which affects the efficiency.

As the compression takes places it causes increase in hydrogen temperature, for that advanced cooling system is need to control heat dissipation. Significant challenges towards the thermodynamics factors it reduces the efficiency of the compression process (Wagner et al., 2014; Rousar et al., 2019) [15, 16]. While compression increases volumetric energy density, hydrogen still demands larger storage volumes than conventional fuels, which is problematic for space-constrained applications like fuel-cell vehicles. Furthermore, energy efficiency declines at higher pressures, and storing hydrogen above 700 bar is uncommon due to technical and cost limitations (Hunt et al., 2020) [17].

3.2 Liquid Hydrogen

Another widely studied method of hydrogen storage is liquefaction, in which hydrogen gas is cooled to cryogenic temperatures to create a liquid form of hydrogen. The concept considerably improves the volumetric energy density of hydrogen and lends itself to large applications in particular.There is significant challenge in liquefaction, as additional cooling must be used to overcome this effect and achieve low temperature (-253°C) required for hydrogen liquefaction. Boiling is highly energy intensive, consuming a large portion of the energy stored in hydrogen, (Li et al., 2020) [18].

Energy requirements to maintain cryogenic temperature:
Once hydrogen is liquefied, it must be stored at cryogenic temperatures to prevent it from returning to the atmosphere This needs sophisticated insulation and cooling work to reduce heat loss and maintain low temperatures. Some heat loss is unavoidable, regardless the use multi-layer containment, resulting a "boil-off" of hydrogen, which can be lost over long time (Montoya et al., 2019) [19]. To maintain cryogenic temperature continuous energy is required. Researcher trying to advance insulation materials and effective technologies for cryogenic cooling, such as magnetic cooling to overcome this issue (Schmidt et al., 2021) [20].

3.3 Solid-State Storage

At low pressure and temperature this method generally used, hydrogen storage it uses the metal hydrides or porous materials. Physics of Adsorption and Desorption in Metal Hydrides: When hydrogen reacts with metals then hydrides formed. These substances soak up hydrogen gas and shape a strong metallic hydride, releasing the hydrogen upon heating (desorption). The ability of steel hydrides to soak up and release hydrogen is ruled by their thermodynamic effects, inclusive of the strain-temperature courting of the hydrogen absorption/desorption cycle. The physics of adsorption and desorption is acute to enhancing the overall performance of these substances. The foremost venture lies within the stability between attaining high hydrogen storage capacities and making sure that the adsorption and desorption processes arise at affordable temperatures and pressures for sensible use (Liu et al., 2017) [21].

Research into Improving Storage Densities and Kinetics:
While metallic hydrides provide the gain of incredibly excessive volumetric storage densities, their hydrogen release kinetics and storage potential are regularly restrained by way of the fabric's microstructure and thermodynamic properties. Improving the kinetics of hydrogen adsorption and desorption, including by way of lowering the activation power for those procedures, is a main area of research. Recent improvements cognizance at the development of recent hydride-forming alloys or composite materials that may operate below milder conditions, inclusive of lower temperatures and pressures, to enhance the general performance of strong-nation hydrogen storage (Züttel, 2003; Lin et al., 2021) [4].Furthermore, steel hydrides, research into different solid-state storage technology, together with chemical hydrides and adsorption in porous substances (e.g., activated carbon or MOFs), is also proceeding. These materials may want to offer alternative solutions to produce better storage densities, stepped forward kinetics, and higher thermodynamic overall performance (Zhao et al., 2020) [17].

4.0 Challenges and Solutions in Production and Storage

Production of hydrogen is important for energy global transition. Though, it has several challenges associated with hydrogen production, storage and transportation. Although hydrogen has the capability to decarbonize industries together with transportation, energy technology, and chemical manufacturing, its powerful integration into the global strength device requires innovation at both the manufacturing and storage stages. In this section, researcher explore the solution to these challenges, focus on developments in catalytic electrolysis, renewable electricity resources for green hydrogen manufacturing and novel hydrogen storage methods.

4.1 Innovations in Electrolysis Catalytic

One of the most widely used techniques for production of hydrogen, splits water into hydrogen and oxygen for usage of energy is the electrolysis. While electrolysis is easy and green, its great use is constrained via the high fee of the compounds and the power requirements of the technique. However, latest improvements in catalytic substances have made enormous development in improving the performance and affordability of electrolysis.

Role of Advanced Materials:

Modern catalysts, including platinum are costly and growing need for substitutes. As a promising aspects, perovskite emerged due to their high catalytic interest and low cost.

These substances, characterized by using their specific crystal systems, show off first-rate performance in both the oxygen evolution reaction (OER) and the hydrogen evolution response (HER), which might be essential for water splitting (Chung et al., 2020) [22].Nanocatalysts, especially those composed of metals along with nickel, cobalt, and iron, are also gaining interest because of their excessive base region and ability to decrease the energy obstacles of electrolysis reactions. To enhance their efficiency and strength catalysts may be tailored on the atomic level, making electrolysis more practical in hydrogen production. Research into enhancing conductivity and preventing catalyst degradation, is a key for development of cost-effective hydrogen production through electrolysis (Xie et al., 2021) [23].Recent improvements in hybrid catalysts that combine the advantages of perovskites and nanocatalysts are displaying awesome promise, as they provide stepped forward overall performance in both electrolysis and gasoline cell programs, driving down fees and improving the scalability of hydrogen manufacturing (Zhao et al., 2022) [24].

4.2 Integrating Renewable Energy in Production

Production of green hydrogen, use of renewable sources is essentialstage. Green hydrogen is produced through electrolysis with the use of renewable resources such

as sun and wind, it offers a sustainable source for hydrogen production. However, successfully integrating renewable strength into hydrogen production structures gives its very own set of demanding situations.
Coupling Hydrogen Generation with Solar and Wind for Green Hydrogen: Solar and wind energy, while sample, are intermittent and geographically variable, which can create instability inside the power grid and have an effect on the stability of hydrogen manufacturing. To achieve with this, advances in electricity storage and grid management technologies are vital for smoothing the addition of renewable power into hydrogen manufacture systems. In specific, coupling hydrogen manufacturing with sun or wind farms lets in for the green use of extra renewable electricity that might otherwise be wasted.One favorable clarification is the improvement of "power-to-fuel" structures, where excess renewable energy is used to supply hydrogen via electrolysis throughout periods of low electricity demand and the hydrogen can be stored or transported for later use (Cozzi et al., 2021) [25]. These methods are being developed to enhance the scalability of green hydrogen and make a contribution to an extra supple electricity grid. Furthermore, innovations in massive-scale battery storage and grid balancing technologies are enhancing the ability to address fluctuations in renewable power supply, making the mixing of renewable assets into hydrogen production systems more reliable and green (Sanz et al., 2020) [26].

4.3 Novel Storage Approaches

Hydrogen storage is big challenge, developments in hydrogen production is crucial for use of hydrogen as energy carrier. But, many new storage devices are being researched to manage these problems and increase the possibility of hydrogen as a clean electricity carrier.Research on Liquid Organic Hydrogen Carriers (LOHCs) and Ammonia-Based Hydrogen Storage: Advanced method to hydrogen storage is the usage of liquid organic hydrogen companies (LOHCs). LOHCs are liquid compounds that can soak up and take-off hydrogen via chemical reactions. These providers provide numerous dedications, consisting of simplicity of storage at ambient conditions, the ability to save hydrogen in liquid form without the need for cryogenic temperatures, and compatibility with existing setup for liquid fuels. LOHCs may be hydrogenated (hydrogen absorbed) and dehydrogenated (hydrogen released) via catalytic processes, making them a promising answer for mobile hydrogen storage (Groll et al., 2019) [27]. Recent studies are targeted on enhancing the effectiveness and reversibility of these reactions and figuring out more fee-effective LOHCs that could operate at lower temperatures.
Alternative promising approach for hydrogen storage is ammonia-based storage, in which hydrogen is saved within the shape of ammonia (NH_3), a solid and easily portable compound. Ammonia may be synthesized from nitrogen and hydrogen with the help of Haber-Bosch system, and it can be used at once as a fuel or decomposed

to introduction hydrogen.Ammonia-based storage gives the gain of excessive volumetric strength density and can be without problems stored and transported in current infrastructure (Danish et al., 2020) [28]. Though, challenges stay in phrases of the efficiency of ammonia synthesis, the eco-friendly impact of its fabrication, and the want for secure coping with and storage because of ammonia's toxicity.Research to improving ammonia synthesis method, environmental aspect, safety and enlightening ammonia technologies for hydrogen release. Developmentsin this section has capability for ammonia as a hydrogen provider (Li et al., 2022) [29].

5.0 Case Studies and Applications

Hydrogen plays crucial role over the global evolution towards clean energy. It is flexible energy carrier throughout several sectors like transportation and electricity technology. Challenges in manufacturing and storage, enhancements in hydrogen technology. In this segment, case studies and applications in which hydrogen is getting used to update fossil fuels, that specialize in hydrogen-powered transportation.

5.1 Hydrogen-Powered Transportation

Hydrogen-powered transportation is one of the most favorable proposals for hydrogen, ability to decarbonize the carrying region, hydrogen is contributor to global greenhouse fuel emissions. Fuel cell electric powered vehicles (FCEVs) are driven by way of hydrogen, which reacts with oxygen in a fuel cellular to supply electricity, water, and warmth. The number one blessings of FCEVs over traditional battery electric powered vehicles (BEVs) consist of faster refueling instances and longer tiers, making them particularly attractive for applications such as heavy-obligation vans, buses, and trains.

Review of Fuel Cell Technologies and Storage Systems in Vehicles: The mobile generation used in hydrogen-powered cars typically is predicated on proton-alternate membrane fuel cells (PEMFCs), that are recognized for extraordinary efficiency and lower working temperature. PEMFCs transform hydrogen into electricity through an electrochemical response, supplying an environmentally friendly opportunity to inner combustion engines (ICEs). One of the principle benefits of PEMFCs is their potential to produce high strength density, that is important for cars, specifically people who require huge energy output, along with buses and vans (Coccia et al., 2020) [30].

The major venture in hydrogen-powered transportation is the storage of hydrogen. Compressed hydrogen storage is presently the most widely used method in automobiles, with tanks running at pressures of as much as 700 bar. Although excessive-pressure tanks made from composite materials inclusive of carbon fiber provide electricity and durability, they also add extensive weight and cost to the vehicle (Zhao et al., 2021) [31]. Furthermore, developments in materials for hydrogen storage, which comprise solid-nation storage and steel hydrides, are being researched to enhance vehicle variety and safety (Montoya et al., 2021) [32]. Additionally, hydrogen refueling set-up stays restricted in lots of areas, which impedes the enormous adoption of hydrogen-powered cars.

A fantastic case is the Toyota Mirai, first heavily produced hydrogen-powered cars, which makes use of a PEMFC and a high-pressure hydrogen storage gadget. In addition to passenger cars, hydrogen-powered buses and vehicles are also being installed in many international cities. In Europe, to minimize urban air pollutants and greenhouse gasoline emissions hydrogen-powered buses are being used in regions like London and Cologne for public transportation (Harrison et al., 2020) [33].

5.2 Industrial Decarbonization

Hydrogen achieves a crucial role in industrial decarbonization, specifically in sectors that depend closely on fossil fuels, cement production, and chemicals. Hydrogen can replace coal, natural fuel, and coke in these procedures.

Role of Hydrogen in Replacing Fossil Fuels in Steelmaking and Chemicals: One of the most renowned examples of hydrogen's capacity in commercial decarbonization is using hydrogen in steel production. The metal industry is one among the most important industrial resources of carbon emissions, roughly speaking because of the usage of coke in blast furnaces. Hydrogen can function a direct reduction agent in place of coke, producing water vapor as opposed to carbon dioxide. The HYBRIT (Hydrogen Breakthrough Ironmaking Technology) task, a collaboration among SSAB, LKAB, and Vattenfall, is a leading case look at proving the use of hydrogen in steelmaking. In this undertaking, hydrogen is used to reduce iron ore to iron, which ominously reduces the carbon footprint of the steelmaking technique (Ness et al., 2021) [34].

Similarly, hydrogen is being explored an alternative for natural gas in the manufacture of ammonia, a key factor in fertilizers. The Haber-Bosch technique, that's traditionally used to synthesize ammonia, is based closely on natural gasoline. By the usage of hydrogen instead of natural gas, the ammonia manufacturing procedure can come to be carbon-impartial. Major companies, which includes Yara International, are leading ammonia plant life that utilize inexperienced hydrogen made from renewable energy resources to lessen the carbon emissions related with ammonia manufacturing (Hansen et al., 2021) [35].

The decarbonization of these commercial sectors is visible as a critical step toward assembly worldwide weather objectives. While the generation remains in its infancy and faces challenges along with the high value of hydrogen and the need for development, growth is being made through pilot projects and enterprise cooperation. The scalability of hydrogen use in industry will depend upon the continuing development of new hydrogen production methods and cost discounts in hydrogen storage and transportation.

Another great region cashing in on hydrogen's decarbonization capability is the chemical compounds industry. Hydrogen is used in the manufacturing of various chemical compounds, including methanol and artificial fuels. By converting to hydrogen as a feedstock in preference to fossil fuels, the chemical substances enterprise should drastically reduce its emissions (Yong et al., 2020) [36]. In addition of renewable electricity assets for hydrogen production can further lessen the carbon footprint of these chemical strategies, aligning them with sustainability goals.

6.0 Future Trends and Research Directions

Hydrogen is essential for the global transition to a sustainable energy future. Challenges in hydrogen production, storage and infrastructure. The future of hydrogen as a strength provider will depend on advances in key regions together with power-green electrolysis systems, the protection and scalability of storage strategies, and the growth of pilot tasks geared toward growing price-powerful hydrogen economies. This segment explores the key future traits and studies directions in these areas, offering insights into how those improvements can deal with the modern restrictions of hydrogen technologies.

6.1 Development of Energy-Efficient Electrolysis Systems

Producing hydrogen using one of the most capable techniques such as electrolysis, frequently renewable energy assets for green hydrogen production. To meet the demand for large-scale hydrogen production, enormous improvements in electrolysis era are needed.

Energy-Efficient Electrolysis: Recent studies has focused on improving the efficiency of electrolysis with the aid of growing advanced catalysts and improving gadget design. The recent improvement, price-powerful materials for the electrolysis process, which includes perovskites, transition metal-based catalysts, and nanostructured electrodes, is a crucial studies direction. These materials have the capacity to lessen strength losses and growth the fee of hydrogen manufacturing, therefore improving the overall efficiency of the gadget (Zhou et al., 2021) [37].

Furthermore, developments in materials, efforts are being made to combine electrolysis structures with renewable power assets, which includes sun and wind, in an extra green way. One hopeful method entails coupling electrolyzers with electricity storage systems that may barrier the irregular nature of renewable energy, confirming a continuous and steady supply of hydrogen (Peng et al., 2020) [38]. Also, upgrades in machine layout and scaling electrolyzers for massive-scale manufacturing are essential to lessen fees and make hydrogen manufacturing more hostile with conventional fossil fuel-based methods.

To optimize efficiency hybrid electrolysis structures that combine special kinds of electrolyzers, together with proton trade membrane (PEM) and anion exchange membrane (AEM) electrolysis. The comprehensive of various technologies decreases cost of electrolysis, making it extra scalable with renewable energy resources (Zhang et al., 2022) [39].

6.2 Enhancing Safety and Scalability of Hydrogen Storage Methods

Hydrogen storage is one of the widestembracing of hydrogen technology. Recent storage methods, inclusive of compressed hydrogen gas, liquid hydrogen, and metallic hydrides, each have their barriers in phrases of energy density, safety, and cost. To realize a sustainable hydrogen economic system, the development of more secure and extra scalable storage technology is critical.

Safety in Hydrogen Storage: The remarkably combustible nature of hydrogen demands the improvement of storage structures that are safe and green. Advances in materials technology have brought about the enhancement of composite materials, polymer tanks, which are operated in high-strain storage structures for hydrogen motors. These materials offer exciting safety, decreasing the risk of hydrogen leaks or injuries (Nielsen et al., 2021) [40]. Still, more research is required to improve the sturdiness and safety of hydrogen storage structures.

Scalability of Storage Solutions:

Underground storage in salt caverns and exhausted natural fuel fields are one of the promising way for large-scale hydrogen storage at low cost. Though, long-term safety and scalability are requiring for advance studies and optimization (Clarke et al., 2020) [41].Moreover, advanced metal hydrides and metal-natural frameworks discovered to offer solution. These materials are designed to soak up and release hydrogen at lower pressures and temperatures, probably supplying safer (Zhang et al., 2021) [42].

Hydrogen Pipelines: Anotherarea of research includes the development of hydrogen pipeline networks. With the help of pipeline network hydrogen may be transported over long distances. The safety, toughness, and cost-effectiveness of hydrogen pipelines are crucial elements. Research is focused on optimizing pipeline materials and corrosion resistance, especially in excessive-pressure programs, to make certain the secure and green transportation of hydrogen at scale (Saeed et al., 2020) [43].

6.3 Expanding Pilot Projects to Establish Cost-Effective Hydrogen Economies

The change to a hydrogen financial system would require giant infrastructure development, in addition to pilot tasks that show the feasibility of hydrogen as a scalable electricity provider. Pilot initiatives are important for trying out new technology in real-global situations, identifying operational challenges, and proving the monetary viability of hydrogen-based structures.

Role of Pilot Projects: Countries and industries all over the world are making an investment in pilot initiatives to set up the infrastructure essential for a hydrogen financial system. For illustration, the European Union has launched the hydrogen Roadmap project targeted at the production, storage, and transportation of hydrogen. These initiatives aim to check innovative answers for integrating hydrogen into present energy structures (European Commission, 2020) [44].

Cost-Effective Hydrogen Economies: Technological improvement of hydrogen fabrication and storage systems, pilot initiatives are exploring commercial enterprise fashions that could assist set up a fee-powerful hydrogen financial system. This consists of emerging mechanisms for subsidizing the initial capital investment in hydrogen infrastructure, developing incentives for using hydrogen in transportation and industry, and integrating hydrogen with renewable power systems. Effective pilot initiatives can serve as blueprints for scaling hydrogen technology and lowering the cost associated with hydrogen manufacturing and infrastructure development (Papadopoulos et al., 2021) [45].

By growing these pilot initiatives and investing in real-global applications, the hydrogen industry can triumph over the limitations to sizeable adoption and transition to an extra sustainable, fee-powerful hydrogen economy. The status quo of nearby hydrogen hubs, where hydrogen is produced, saved, and applied across various sectors, will be a key element in reducing the general price of hydrogen and increasing its marketplace competitiveness.

7. Conclusion

Hydrogen play a crucial role in the energy transition globally. In this paper we presented current situation of energy carrier sources and hydrogen as an alternative, physics of hydrogen as an energy carrier, challenges in hydrogen production with various methods their advantages and limitations, challenges in hydrogen storage and solution, applications, future trends and research directions. Hydrogen is the key runner for future clean energy, due to high energy content. Its role as an energy carrier holds to transforming global energy systems, especially in climate change and achieving sustainable energy goals. This paper highlights challenges in hydrogen production by shifting from traditional methods to advanced method like green hydrogen production method, also needs some advanced materials, cost reduction, environmental sustainability. Recent Advances in hydrogen production, researcher focus towards use of advanced materials such as perovskites and nanocatalysts,shifting towards the use of renewable natural resources. Challenges in hydrogen storage system, current hydrogen storage method like, compressed hydrogen gas, liquid hydrogen such method have limitations over safety, efficiency and cost related issues. To overcome these challenges researcher exploring novel storage methods such as advanced metal hydrides, development of composite materials and one of them is use of liquid organic hydrogen carriers (LOHCs)these novel method improving storage capacity, safety, efficiency and reduce the cost. Hydrogen role as an energy carrier is demonstrated in various real-world applications. In Industrial decarbonization, transportation, hydrogen powered vehicles, electric cars, buses and trucks is being developed as alternative combustion engine vehicles. Future trends likely to focus on improving energy efficiency, reducing cost of hydrogen production and scaling storage technologies, establishment of hydrogen infrastructure including refueling stations, storage facilities and cost effectiveness.

Author Address:
1Assistant Professor, Department of Physics, VPMK's Art's Commerce and Science College, Kinhavali, Thane, Maharashtra, India
2Assistant Professor, Department of Physics, Shri Vasantrao Naik Mahavidyalaya, Dharni, Amravati, Maharashtra, India
3Professor, Department of Physics & Electronics, MSP's Shri Shivaji College, Parbhani, Maharashtra, India

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