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# Current Developments on the Application of Hydrogen in Industry: A Review

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## ABSTRACT

The worldwide transition in energy utilization to a society that is “carbon-neutral” demands a major revamp of power generating and distribution networks. Notwithstanding, in the great drive for the growth of renewable energy that is clean and environmentally safe, hydrogen's incorporation into energy networks is currently understudied. The state of the current art and prospects for the future, including prospective applications of hydrogen technologies in energy are examined in this overview. The findings demonstrate the fact, which portrays continual efforts to increase performance, technological perspective, and increases in scale. Finally, governmental support is of great importance and necessity if allowance is to be made for a cost-competitive hydrogen economy.

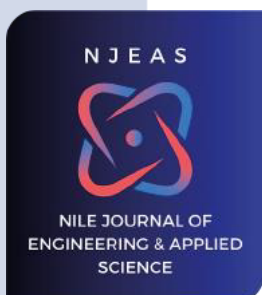
**KEYWORDS:** Hydrogen; Renewable Energy; Steel Development; Power Generation; Carbon-Neutral

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## 1 | INTRODUCTION

Ecologically, friendly, safe, and sustainable supplies of an efficient amount of energy are critical to humanity's survival and high quality of life, but their provision is fraught with social, political, environmental, and economic issues. One generally accepted fact is that no one source of reliable energy can take precedence over and regulate the entire energy market of the world, and so an energy model which is a mix has generally been adopted that can gain from the ease of accessibility of useable resources or from the choice of energy resources importation [1].

Hydrogen is of all the elements, the most simple, lightweight and regularly occurring chemical element. Each atom of hydrogen contains just a proton [2]. It is found in water, hence practically in all organic molecules. At atmospheric temperatures and pressures, hydrogen is gaseous, but at  $-423\text{ }^{\circ}\text{F}$  ( $-253\text{ }^{\circ}\text{C}$ ), it becomes liquid. However, because hydrogen is naturally bonded to other elements at ambient temperatures, the hydrogen molecules must be set apart from them to produce pure, unbound hydrogen and because it produces no damaging greenhouse emissions, hydrogen tomous climate protection potential as an energy carrier.

Greenhouse gases (GHG) trap heat and warm the globe, and the primary source of GHG from human activity is the use of fossil fuels when obtaining or producing power, generating heat, and transportation operations [2]. The ozone layer works as a cover, stopping the sun's dangerous ultraviolet radiation from getting to the earth's surface. The ozone layer's depletion owing to the creation of carbon dioxide from carbon monoxide's reaction with excess atmospheric oxygen lowers the ozone layer's shielding function, resulting in skin burns and other skin diseases.

Carbon dioxide is also a warm gas hence resulting in global warming. The repercussions of global warming, to mention a few are; the melting of ice in the world's coldest places, as well as climate change concerns such as unprecedentedly extreme rainfall and an increase in atmospheric temperature [3–6].

Since hydrogen is a critical component transition of the energy sector, it is important to make it feasible economically, reduce its resource needs and optimize its decarbonization impact. As the hydrogen momentum grows, it becomes evident that policymakers must prioritize decarbonization in order for hydrogen to fulfill its promise as a crucial solution in the global clean energy transition, contributing significantly to net zero emissions.

There are several techniques for producing hydrogen, all of which create the colorless gas hydrogen. Despite this, it has been given a variety of colorful names, including green, grey, blue, and turquoise hydrogen [7]. These are essentially color codes that are used to distinguish distinct hydrogen generation technologies and the energy carriers connected with them. If no  $\text{CO}_2$  is created during the manufacturing process, this type of hydrogen is called green hydrogen while if the  $\text{CO}_2$  is instantly and permanently stored, this is referred to as blue/turquoise hydrogen, with this, zero emissions might be achieved [8].

Renewable energies may be stored as hydrogen and delivered using the existing gas infrastructure. The current gas infrastructure can carry hydrogen. There are several hydrogen transportation modalities, with the mode of selection being mostly dictated by the physical state of the gas. Because hydrogen is present as a gas at ambient temperatures, the most commonly employed method is the direct injection into the existing gas grid or new hydrogen pipelines, either when it's still pure or combined with "natural gas".

In the early nineteenth century, the German gas infrastructure called German town gas was utilized to transport hydrogen containing 50% hydrogen. Hydrogen may also be delivered in liquid form, either by sea or in tank trucks, which involves cooling the gas to  $-253\text{ }^{\circ}\text{C}$  and storing it in specific transportation containers [9]. Another alternative is to link hydrogen to other molecules, such as methane, ammonia, or methanol, for subsequent transportation.

The capacity of an energy system determines its efficiency. Green hydrogen

generation needs a certain quantity of energy. Modern electrolysis procedures need roughly 25%, which may be decreased to 10%, allowing up to 90% of the initial energy input to be accessible as hydrogen following electrolysis. The process efficiency can be increased even further if the waste-heat created by electrolysis is used to heat companies or buildings, for example. Such waste-heat is easily conveyed by moving it into a heating network, for example, to provide green heat to households and businesses.

To understand why hydrogen, despite being given a certain energy loss, must be a major player in building the energy system for our future, it is crucial to go beyond an individual plant and instead evaluate the entire system and its efficiency as a whole. The present development, exploitation and transportation of hydrogen pertaining to the industry is the focus of this review. Figure 1 expresses the increase in the demand of hydrogen over the recent past.

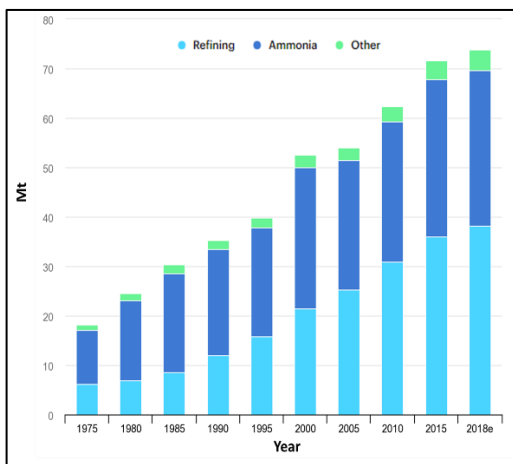


Figure 1: Global demand for pure hydrogen, 1975-2018 [10]

The transportation industry contributes significantly to overall CO<sub>2</sub> emissions. As a result, mobility is one of the sectors that require the most investment to achieve decarbonization and energy transition, which is done by optimizing the efficiency of cars and transportation systems. Renewable-source hydrogen is a possible alternative for long-term transportation. It may be used in fuel-cell vehicles such as automobiles, trucks, and trains, as well as a main material in the production of synthetic fuels for maritime and aviation transportation.

In addition to the, there has been an increased perception of the necessity of diversification of the use of hydrogen in various aspects of industry.

Figure 2 shows how more interest and requirements are placed on Hydrogen from different regions of the world.

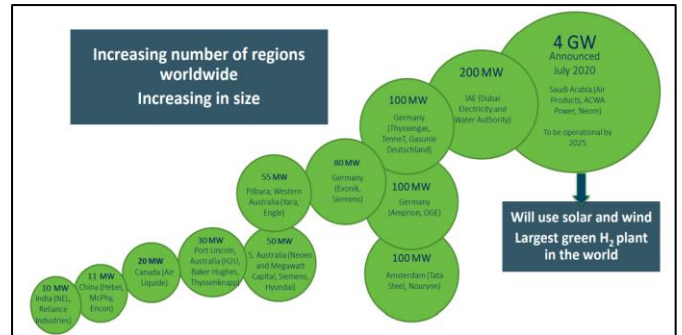


Figure 2: Increase interest in hydrogen energy [10]

### 1.1 Hydrogen and Energy Utilization

Hydrogen is an instrument of power that needs to be generated from yet another component. Hydrogen might well be produced (split) from an assortment of sources, such as water, fossil fuels, or biomass, and used as an energy or fuel source. Hydrogen has the highest calorific value by weight of any conventional fuel but the lowest by volume. The act of producing hydrogen by separating it from other elements in molecules requires more energy than what hydrogen provides when converted to usable energy.

Conversely, because hydrogen has a high energy content per unit of weight, it is useful as an energy source/fuel and is utilized as rocket fuel and in fuel cells to generate electricity onboard some spacecraft. Hydrogen is not just an energy fuel for temporary usage, but it has the potential to become more frequently used in the long term [10].

Power-to-hydrogen is a potential method of storing fluctuating Renewable Energy (RE) to create a 100% renewable and sustainable hydrogen economy [11]. The hydrogen-based energy system (hydrogen energy cycle) is divided into four primary stages: production, storage, safety, and use as shown in Figure 3.



Figure 3: Stages of Hydrogen Energy System

### 1.2 Hydrogen Production

The production process for hydrogen and “its technology selection is influenced by the type of energy and feedstock available, as well as the end-use purity required. As a result, purification technologies are being integrated into industrial processes for system integration, energy storage, use, and RE export. The hydrogen production process is described in Figure 4.

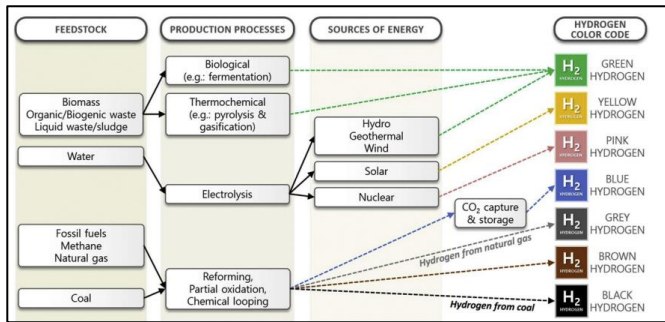


Figure 4: Hydrogen production routes [12]

[11] investigates the interconnections and interdependence of hydrogen-generating pathways and associated technologies on the other constituents of its energy system. Even though hydrogen is an energy carrier of net zero-carbon-emission when it is being consumed, its sustainability is dependent on how clean the production route is and the utilized energy feedstock to manufacture it. As a result, ensuring the origin of hydrogen is critical if hydrogen is to be considered clean energy. For further inquiry and development, a unique concept is proposed as a hydrogen cleanness index coding as shown in Figure 5.

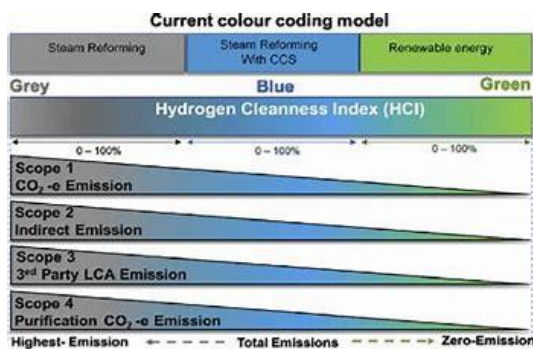


Figure 5: HCl coding [13]

### 1.3 Hydrogen Storage

Hydrogen energy storage is a current and emerging topic. Storage practices are just as

important as manufacturing processes. These processes are critical in the hydrogen economy. The goal of hydrogen energy storage is to ensure its safe and efficient use anywhere and anytime [14]. There are three hydrogen storage techniques. Physical storage technologies include compressed gas storage, cryogenic liquid hydrogen storage, and solid-state storage. Hydrogen storage materials should be economically viable, have a low operating temperature, and have a high hydrogen storage capacity [15].

The most common approaches are compressed gas and liquid hydrogen storage. Solid state storage technology is evolving and will become more widely used in the coming years [16]. Hydrogen can be compressed to 700bar in suitable structures and held as a gas in cylinders, containers and underground cavities [17]. Steel, aluminum and carbon fiber reinforced plastic composite materials are used to manufacture compressed gas containers [18]. The type of hydrogen storage depends on the volume of hydrogen to be stored as well as the storage time.

The underground hydrogen storage project in Romania is one of the efforts for efficient hydrogen storage [19].The purpose of the research was the storage of hydrogen in underground salt caves. The main advantages of this approach are simple technology and fast filling and draining. The disadvantage is that the volume density of hydrogen gas does not increase with increasing pressure [20].

The density of hydrogen held as a liquid is higher than that of a compressed gas, so it holds more energy per unit volume [8]. Low-pressure liquid hydrogen storage equipment is inexpensive [21]. While liquid hydrogen can be maintained at -253 degrees Celsius, compressed hydrogen gas can be stored at room temperature [22].

The boiling point of hydrogen is low in liquid hydrogen storage technology. Specific containers with isolation techniques are required to ensure hydrogen efficiency [23]. Due to the risk of continuous boiling due to the low boiling point of hydrogen, this approach is designed for short-term storage [21].

Large quantities of hydrogen can be stored in a compact container using solid state storage. It is better than other methods because it requires less space [17]. A solid-state hydrogen storage method is one in which hydrogen atoms or molecules are mixed with other substances.

Nanostructured materials and hydrides are two types of solid-state deposition. Due to the low density of the storage process, the hydrogen storage efficiency of nanostructured materials is low [8]. As nanotechnology advances, nanostructured materials will be able to store more hydrogen.

### 1.4 Hydrogen Utilisation

Table 1 below shows the different ways that hydrogen is used:

Table 1: Some Areas of Application of Hydrogen and their Limitations				
S/N	Area	Application	Limitation	Reference
1	Exploration in Space	Liquid hydrogen was originally employed in the chronic stage of Saturn rockets during NASA's Apollo program. Others include United Launch Alliance, Boeing, and Blue Origin.	Hydrogen Energy is costly. There is a lot of difficulties with Storage. It is not the most secure source of energy. Due to its light weight, it is difficult to move about. Separation from oxygen necessitates the use of non-renewable resources. Currently inadequate to sustain the global population.	[13]
2	Aviation	The adaptation in use of hydrogen fuel cells in projects like the <a href="#">Pathfinder and</a>	it is difficult to move about. Separation from oxygen necessitates the use of non-renewable resources. Currently inadequate to sustain the global population.	[13]

		<a href="#">Helios</a> unmanned long duration aircraft.	ates the use of non-renewable resources. Currently inadequate to sustain the global population.	
3.	Public Transportation	Hydrogen fuel cells are also being studied for other public transportation applications such as buses and trains.		[27]
4.	Personal Transportation	Major automakers are developing hydrogen fuel cell vehicles (FCVs) for personal usage.		[9]
5.	Power Generation	Hydrogen is being utilized for cooling power plant turbines; it also offers a viable method of electrical grid stability.		[28]
6.	Backup Power Generation	Locally utilized as uninterruptible power supply (UPS) for crucial constant power supply.		[29]

### 1.5 Safety in Hydrogen Production

Safety is a priority in hydrogen production, storage and transport processes. With careful storage and delivery of hydrogen, as with other fuels, there is no danger of burning or exploding. The flammability and explosiveness of gasoline exceeds that of hydrogen [16]. When gasoline is spilled, the spilled fuel clumps together and burns more easily. When combustion occurs, deadly effects such as explosions follow. If there is a leak in the hydrogen tank, it will dissipate as a gas, reducing the possibility of ignition.

As there is no carbon in combustion, the fire flickers rapidly. If adequate precautions are taken, it is less harmful than hydrogen gasoline. The number of hydrogen fuel cell cars on the road is increasing every day. As a result, concerns about the safety of hydrogen have grown in recent years. Using hydrogen instead of gasoline or diesel poses a number of risks in transportation [24]. Hydrogen has a wide burning range, low ignition energy, and the hydrogen flame is barely visible in daylight [25].

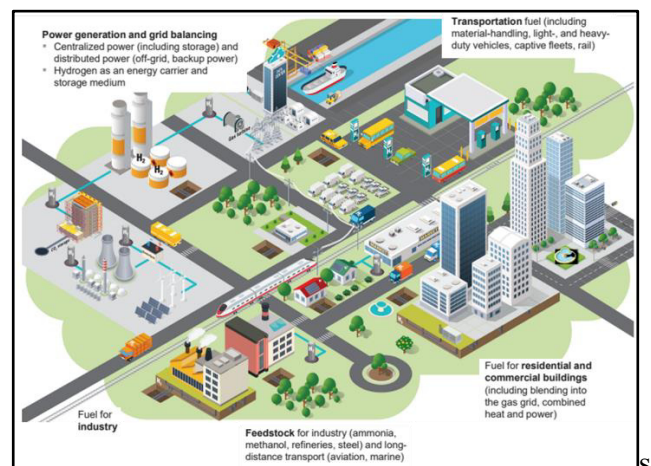
In vehicle tanks, hydrogen is kept as a compressed gas at a pressure of 70 MPa [26]. Due to thermal insulation and boiling problems, liquid hydrogen storage is not ideal for vehicles. Vehicles do not yet have fixed storage space. Hydrogen contained in automobiles as a compressed gas has the potential to explode. In order to prevent similar explosions in cars, pressure-release mechanisms should be placed in hydrogen tanks. Under high pressure conditions, this gadget reliably relieves pressure.

## 2 | HYDROGEN ENERGY AND ITS APPLICATION IN THE INDUSTRY

Hydrogen is primarily employed in industries across the world, and at the moment, important research is being conducted to that regard. Hydrogen energy is mostly employed in the chemical and oil industries and for the processing of steel. The majority of hydrogen in the oil and chemical industry is utilized for hydrogenation, hydrocracking, and desulfurization [30].

Ammonia is also produced in the chemical industry using hydrogen and the same goes for methyl alcohol, with hydrogen accounting for the majority of the volume in ammonia synthesis. In the globe, 60% of hydrogen is utilized in the manufacture of ammonia, with China accounting for 80% [31]. The quantities of hydrogen utilized in oil refining is only second to the amount used in ammonia production. Hydrogen is widely utilized in the hydrogenation and desulfurization of naphtha, gas oil, and fuel oil, as well as in boosting the flame height of aviation fuel and hydrocracking.

Hydrogen serves two functions in the steel industry. Hydrogen is a byproduct of the steelmaking process. This way of manufacturing hydrogen is less expensive, but the hydrogen generated is frequently utilized to aid combustion. Secondly, during cold rolling, it acts as a protective gas. Furthermore, as the carbon emission restrictions become increasingly severe, an increasing number of steel mills, instead of carbon are beginning to employ hydrogen power for metallurgical processing. The basic idea here is that hydrogen substitutes carbon in metallurgical processing units because of its capacity to lower carbon emissions [32]. Figure serves as a pictorial representation of industrial utilization of hydrogen.



**Figure 6: Hydrogen in Industrial Application [33]**

## 2.1 Hydrogen Energy Systems

### 2.1.1. Power Systems Application

Hydrogen energy is being more widely used in energy storage and delivery, and it has enormous promise in energy systems that are in nature. Here, it is primarily employed for power storage and in the joint supply of heat and power [2].

For the fact that Hydrogen is used to store and transfer energy in a variety of applications, this section introduces and demonstrates four popular uses of incorporating hydrogen into power systems. These applications include energy storage, power-to-gas systems, fuel cell co- and tri-generation, and vehicular applications. Because of hydrogen's large capacity for storage, energy storage based on hydrogen has gained attraction recently. It can meet demands for energy storage across a wide time frame [34].

Throughout the world, several hydrogen energy storage projects have been undertaken, revealing the possibility of large-scale industrial utilization [23]. It has provided an all-green solution for providing electrical loads by utilizing photovoltaics (PVs) and wind turbines, as well as hydrogen storage, batteries, and super-capacitors to meet the IT infrastructure's inflexibility and uncontrollability. Batteries and super-capacitors are employed to satisfy short-term and quick-reaction needs

Voltage support is another function that hydrogen equipment may provide because separate devices are joined to the grid and electrolyzes may have to be adjusted to meet local voltage support requirements [35]. This is accomplished by providing or absorbing reactive power via an inverter or rectifier control. In the event of a blackout, another option is a black start [36]. A traditional power generator set is often used to restart the working power plant. A fuel cell may also do this with no emissions or noise. Providing a variety of services and selling hydrogen for other purposes appears to be essential to enable the viability of hydrogen installations in most research [37].

**Table 2** provides further information on the power systems applications of hydrogen.

**Table 2: Power Systems Applications and their Limitations**

S/N o.	Area of Application	Applicable Technologies	Limitations	References
1.	Energy Storage	Use of porous materials for Hydrogen-based energy storage.	Inaccuracies in data acquisition as measurement and replicability.	[38–41]
		Metal Hydrides	Stability or instability of metal hydrides upon heating to several degree centigrade.	[42]
2.	Power-to-gas Systems	Electrolyser technology	-The exchange membrane materials for the anions are relatively quite expensive. -The membranes' ionic resistance is also relatively high. -There is (parasitic) loss of energy that can be considered to occur across the entire system.	[43–44]
3.	Fuel-cell Technology	Proton exchange membrane s fuel cells	Lack of codes, technical design laws, implementation methods, and technical standards are among the system integration difficulties.	[29]
		Direct methane fuel cells		
4.	Vehicle Applications	Hydrogen-fuelled internal combustio	-Concerns about the safety of	[45–46]

	n engines	hydrogen-powered cars	
	Hydrogen fuel-cells	-Hydrogen transport and distribution constraints. -Hydrogen storage tank fitting material	

**2.1.2 Transportation Application of Hydrogen**

Already, energy from hydrogen-based technology is being used in the transportation sector. This representation occurs as Hydrogen Fuel Cells (HFC) and Hydrogen Internal Combustion Engines (H2ICE) [35]. Fuel-Cell Vehicles (FCVs) generate energy through electrochemical processes using hydrogen and oxygen. The advantages of hydrogen FCVs include their high efficiency, lack of harmful emissions (water vapor is the only emission that is harmless when compared to the emissions produced by the combustion of fossil fuels, such as nitric oxide, nitrogen dioxide, carbon dioxide, and sulfur dioxide), quiet operation, and modularity.

Alternatively, the benefits of H2ICEs include reliance on a mature industry with a large production infrastructure, the ability to offer "flex-fuel" to aid in the transitional period, which could aid in the deployment of the hydrogen infrastructure, lower hydrogen requirements compared to HFCs, ultra-low emissions, higher peak and part load efficiencies in comparison to conventionally fueled ICEs, and they are not dependent on rare materials [36].

The distinct motor technology distinguishes hydrogen-powered automobiles from conventional vehicles. The hydrogen in the car's hydrogen storage tanks and outside air is placed into the fuel cells for electricity generation which in turn, drives the vehicle engine. Having accumulators to support power sources of the fuel cells can yield some power increase and at the same time, simultaneously act as an energy recycling device, improving overall vehicle economy; this is a step that can be taken to solve concerns with fuel cells such as poor dynamic response and insufficient maximum output.

Fuel cell vehicles, on the other hand, are now receiving government support in China [8].

Hydrogenation station provides hydrogen that utilizes vehicles that employ the use of fuel cell. This facility is crucial and is important in the propagation of vehicles that are fueled therein. The section where hydrogenation takes place is responsible for ensuring that the drying system is adjusted and then, dehydrating/drying the hydrogen into gas; the hydrogen is then passed into the hydrogen storage which consists of highly pressurized containers through the hydrogen compressor.

The hydrogen compressors, in turn, fill up the fuel cells, utilizing the hydrogen injector. A good number of research and development have been conducted in the various modes of utilization and/or application of Hydrogen for transportation and table 4 serves as an exhibit into some of said work.

**Table 3: Summary of some recent research contributions on the application of hydrogen in transportation.**

S/N	REFERENCE	APPROACH	COMMENTS
1.	[47]	An overview: Current progress on hydrogen fuel cell vehicles	This research examines the present status of fuel cell electric vehicles (FCEVs), as well as the concepts of (proton Exchange Membrane) PEM fuel cell technology and technical issues in automotive applications.
2.	[48]	Development and application of fuel cells in the automobile industry	Recent advancements in fuel cell technology from the standpoint of the vehicle industry and addresses current constraints impeding Fuel cell vehicles (FCEV) implementation are examined. The current state of fuel cell

			technology, regulations, and commercial prospects for FCEVs, as well as recent FCEV advancements, are discussed.
3.	[49]	Estimation of Liquid Hydrogen Fuels in Aviation	The needed volume of liquid hydrogen fuel and overall cost of liquid hydrogen were analyzed using liquid hydrogen fuel models of an airplane and all aviation sectors when various environmental criteria are met.
4.	[50]	Conceptual design and optimization of a general aviation aircraft with fuel cells and hydrogen	A clean sheet aircraft design and optimization is performed in this work to evaluate the potentials for a general aviation aircraft using hydrogen fuel cells. The goal is to design an efficient airplane configuration that includes all drive train components such as hydrogen tanks, fuel cells, and electric motors, as well as passenger seats and cargo capacity.
5.	[51]	Hydrogen fuel cell heavy-duty trucks: Review of main research topics	This document summarizes the known information about heavy-duty fuel cell trucks, as their deployment, together with battery electric vehicles, should be regarded a

			complementary strategy to reducing CO2 emissions.
6	[52]	Recent progress in hydrogen fueled internal combustion engine (H2ICE) – A comprehensive outlook	The examination of the physical, chemical, and combustion properties of hydrogen, as well as engine design requirements. Recent trends in hydrogen engine and vehicle development strategies, such as port fuel injection and direct injection technologies, are assessed in terms of engine performance and emissions.
7.	[53]	A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges	This paper presents a thorough assessment and critical analysis of the most recent research findings, as well as an outline of the future problems and potential associated with the use of hydrogen to power internal combustion engines (ICEs).
8.	[54]	Review on blended hydrogen-fuel internal combustion engines: A case study for China	This review focuses on China's research and development of mixed hydrogen-fuel internal combustion engines since the turn of the century.
9.	[29]	Recent advances, unsolved deficiencies, and future	This literature study highlights the current state, technological achievements,

		perspectives of hydrogen fuel cells in transportation and portable sectors	and future prospects of hydrogen fuel cell technology in both the transportation and portable industries.
10.	[55]	Hydrogen fuel cell vehicles; current status and future prospect	A significant advancement in hydrogen fuel cell engines is discussed in this paper to examine the viability of using hydrogen as a key fuel in transportation systems.

**3.0 ANALYSIS OF CAPACITY CONSTRAINTS OF HYDROGEN ENERGY DEVELOPMENT**

In China, the energy sector pertaining to hydrogen is still in its early stages, with many flaws in its implementation. The primary techniques are outdated, hydrogen is expensive, the framework is inadequate, and yardsticks are lacking [54]. Furthermore, in terms of standards, the hydrogenation process is not permitted in hydrogenation stations to ensure that hydrogen and its chemicals are safely handled.

It should also be noted that, because there are no standards nationally enforced, hydrogen meant for commercial usage can only be transferred in gaseous form; the set back of this process is that it is five times more expensive than hydrogen in liquid form in terms of storage and delivery. Asides from the cost, the hydrogen energy business lack industrial standard and technical restriction which impedes product acceptance and expansion.

**Table 4a** reviews some of the work done, findings, recommendations, and gaps on hydrogen.

Author(s)/Year	Title	Major work done	Findings
[9]	"Achieving sustainable development goals through adoption of hydrogen fuel cell vehicles in India: An empirical analysis"	Adoption of Hydrogen fuel cell cars (HFCVs) and their direct and indirect influence on SDGs demonstrated using 358 valid sample responses from a pan-India survey.	1.The use of HFCV has a beneficial influence on the SDGs. 2.Policy consequences drastically alter public perception of high costs and infrastructure preparedness.
[18,23]	Hydrogen energy, economy and storage: Review and recommendation	A quick discussion of hydrogen as an ideal sustainable energy carrier for the future economy, with storage as a stumbling barrier.	Hydrogen is a promising, cost-effective, clean, and long-term energy carrier. <ul style="list-style-type: none"> <li>The storage of hydrogen is a persistent barrier to its incorporation into the global economy.</li> <li>Metal hydrides have the potential to connect hydrogen storage to a future hydrogen economy.</li> </ul>
[2]	Hydrogen energy systems: A critical review of technologies, applications, trends and challenges	A look at the current state and future prospects of hydrogen technologies, as well as their	Experimental data and hydrogen deployments are used to show the features of electrolyzers and fuel

		use in power systems for hydrogen generation, re-electrification, and storage.	cells.
[56]	Review of the current technologies and performances of hydrogen compression for stationary and automotive applications.	A summary of the main traditional hydrogen compression methods' current status of development	Compression technology's basic working principles and possible performance levels.
[57]	Hydrogen in energy transition: A review	Expression of hydrogen's progress as a major component of the future green energy society.	Recent advances in hydrogen technologies, their social, industrial, and environmental significance, as well as the stage of transitioning economies in both advanced and developing nations.

**Table 4b: Reviews of some of the work done, findings, recommendations, and gaps on hydrogen.**

Recommendation	Knowledge gap	Perceived usefulness
To relieve infrastructural constraints, gasoline sellers should build additional hydrogen filling stations around the country.	Improve the understanding of public knowledge of hydrogen energy by examining survey data obtained from individuals	Giving all stakeholders a crucial viewpoint on hydrogen energy.

Green hydrogen generators, fuel cell manufacturers, HFCV makers, and early adopters of HFCVs in India should be financially rewarded by governments at all levels.	using basic statistical techniques.	
More targeted effort should be done based on the findings with enormous potential to pave the way to a hydrogen economy.	Improving the kinetics of potential hydrides and researching novel materials and/or technique combinations to generate high hydrogen density storage with quick kinetics at suitably low temperatures.	Provision of sufficient evidence from the literature and research data to show the feasibility and great benefits of storing hydrogen in current metal hydrides.
Policymakers should strengthen the policies that bring hydrogen to today's markets and encourage the development of hydrogen-integrated energy systems.	To allow a cost-competitive U, ongoing work on performance improvements, scale ramp-up, technological prospects, and political backing are necessary.	Based on the literature review, a variety of improvement is required soon.
The availability of many hydrogen compression methods encourages the development of new creative and ecologically beneficial energy-use solutions.	Transitioning away from fossil fuels and making an important contribution to sustainable development.	Hydrogen's application and significance in energy usage
Viable implies getting through the energy transition and executing its hydrogen strategy.	Efficient and effective ways of expanding the hydrogen economy through enhanced energy	The growth of hydrogen infrastructure reflects progress in hydrogen utilization.

	techniques.	
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#### 4.0 | SUMMARY

The findings presented and reviewed above have provided valuable insights into the application of Hydrogen in various sectors. The recommendations and conclusions drawn from this are presented below:

##### 4.1 Recommendation

To some extent, the development of hydrogen-powered energy systems has reached some considerable extent yet there is still considerably tremendous space for technological advancement. Based on a review of the literature over time, a range of improvements is expected soon. It should be emphasized how continual efforts should be made to minimize the capital costs of systems in many dimensions, while maintenance costs should be greatly lowered and tend to approach the set objective shortly.

All these should be born to mind while boosting system efficiency and durability upon which should be researched on and developed [2]. Additionally, regulators should reinforce the procedures that allow hydrogen to be delivered to today's markets and support the development of hydrogen-integrated energy systems.

There exists the requirement to largely make more investments in the research of hydrogen production and development of fuel cells; also including hydrogen storage, and related delivery techniques to strengthen their infrastructure, seek solutions and advancements, reduce expenditure, and waste, and set nationally applicable standards to govern the industry. When this is achieved, we be able to effectively address the constraints of energy from hydrogen and build the groundwork for an efficient system that is also clean, based on secondary energies.

##### 4.2 Conclusions

Hydrogen is helping to decarbonize a variety of industries, including manufacturing, transportation, hydrogen-electricity coupling energy systems and power generation; hence it has

found widespread use in a variety of these industries as studies have been conducted in order to construct models and devise control and optimization procedures. Attempts have been made to speed up the process of turning this potential into reality.

There have been serious attempts to ensure that this technology finds more usage. In terms of production, re-electrification, and storage, this article analyzed the essential technologies that permit hydrogen integration into energy sectors. The background uses are highlighted and the potential of hydrogen to store and transport energy is also addressed.

The advancement of technical preparedness allows for large-scale deployments of renewable hydrogen electrolyzers in the future. This article also noted that the current state of hydrogen generation; hydrogen's widespread use in industrial applications; and the consumption of water and rare materials have all hampered progress from a sustainability standpoint.

Furthermore, the efficiency and durability of electrolyzer systems and fuel cell systems have not been achieved, resulting in significant operating and maintenance costs.

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**Conflicts of Interest:** The authors declare that they have no conflicts of interest to report regarding the present study.

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