RECENT ADVANCES IN GREEN HYDROGEN USED IN THE TRANSPORTATION INDUSTRY

"Green" hydrogen is considered an essential energy source and is becoming increasingly popular as a sustainable energy source, particularly in transportation. Green hydrogen is created by splitting water into hydrogen and oxygen through electrolysis, which uses renewable energy sources. Because this process does not use fossil fuels, the hydrogen it produces is considered "green" because it's an environmentally friendly substitute. Since then, there have probably been more advancements in applying green hydrogen in transportation.

The Green Hydrogen Revolution

Current trends indicate that hydrogen will significantly lower greenhouse gas emissions in the transportation industry. It can be advantageous for heavy-duty transportation applications, such as long-haul trucks, locomotives, and ships, where other means of transport are incompatible with current battery technology (e.g., the required battery weight would be too substantial). Fuel cells reduce vibrations from moving parts, increasing the vehicle's efficiency and quietness. Hydrogen fuel is perfect for fueling heavy-duty tractor-trailers and public transportation buses, which can travel hundreds of miles simultaneously since it enables vehicles to travel farther between refills. Long-term energy storage is another capability of hydrogen. Hydrogen could help balance the grid's intermittent supply and fluctuating demand as more renewable electricity from solar and wind technologies is added. It will take some time to integrate hydrogen fueling infrastructure into our local and national roadways like traditional fueling stations were combined and BEV charging stations are currently being integrated[1].

Hydrogen is a fuel option with minimal carbon emissions. Being abundant throughout the planet and the universe, it is produced using various domestic resources such as natural gas, biomass, coal, waste, and renewable power sources. It must also be compressed or liquified due to its lightweight, making transport and storage challenging for many. Future trends anticipate hydrogen becoming cheaper and competitive with other energy sources over time and with continued use. A viable method for producing hydrogen without carbon dioxide from nuclear and renewable resources is electrolysis. The process of electrolysis involves splitting water into hydrogen and oxygen with the help of electricity. This reaction occurs in a device known as electrolyzer. Electrolyzers can be large-scale central production facilities directly connected to renewable energy sources or other non-greenhouse-gas-emitting forms of electricity production, or they can be small, appliance-sized devices ideal for small-scale distributed hydrogen production. With today's technology, the efficiency of electrolysis in producing hydrogen is typically around 75%. It thus requires 52.5kWh to produce one kilogram of pure hydrogen fuel with a specific energy content of 39.4kWh[2]. Increasing the electrolysis efficiency to 95% means a kilogram of fuel can be produced with just 41.5 kWh of energy. This is a significant improvement over the old electrolysis method and the fossil-fuel-based hydrogen production methods, which are about 75% efficient at best[2].

Hydrogen's full potential is not realized until it transforms into derivatives. Almost any molecule can be created when hydrogen and carbon from CO_2 are combined to form hydrocarbons. It can be used to create ammonia, which has two uses: it can be fuel for new uses like shipping, or it can be used as feedstock for fertilizers, the majority of its current use. It can also be used as a reducing agent to replace coal in producing iron and create methanol and synthetic fuels. Its energy density is further enhanced upon conversion into these commodities, rendering long-term storage and long-distance transportation economically viable. Consequently, switching to hydrogen derivatives opens up trade in renewable energy worldwide[3].

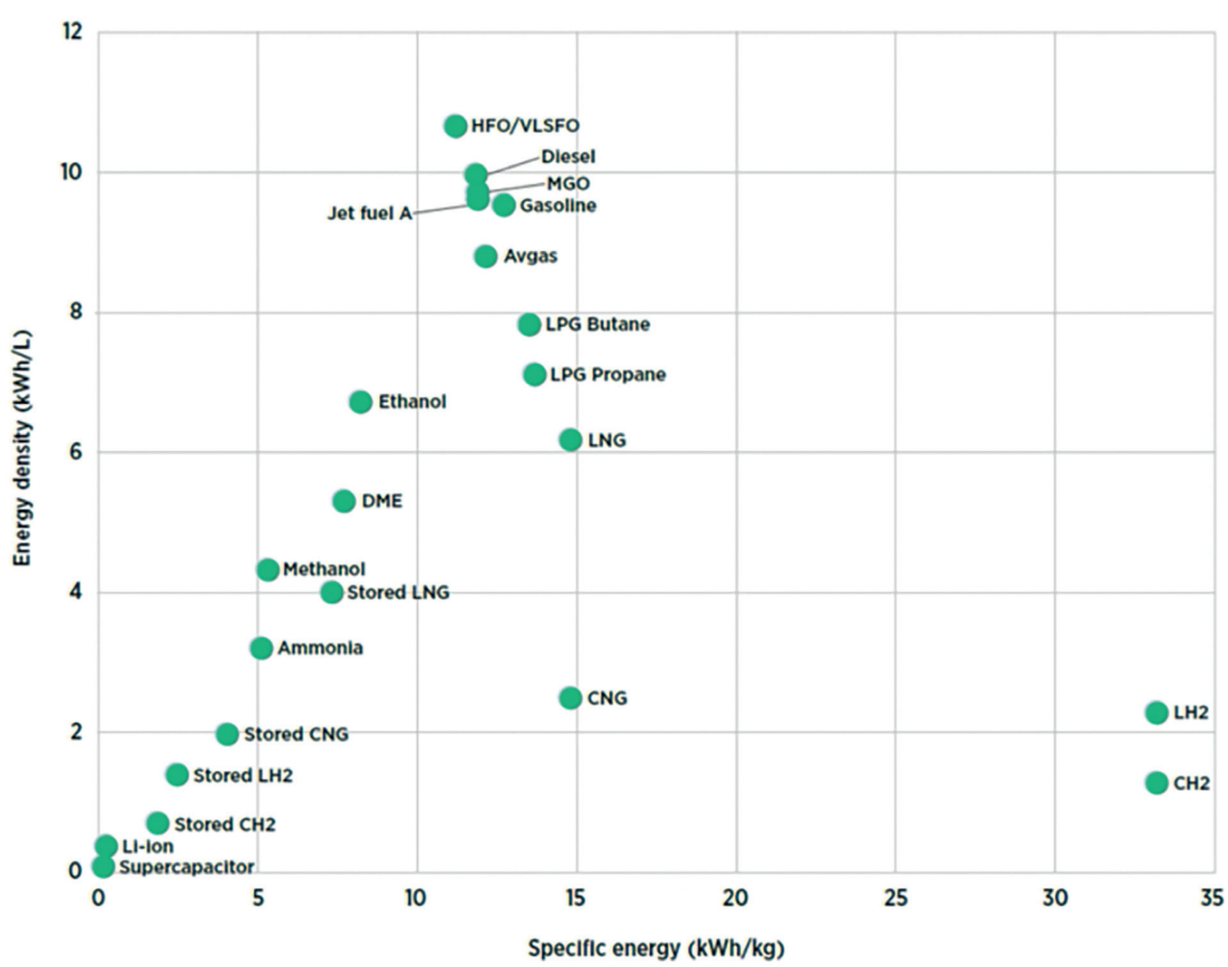

Figure 1: Energy density and specific energy of various fuels and energy storage systems[3]

Many nations see hydrogen as the key to managing energy in the future and they are supporting the introduction of hydrogen technologies aimed at achieving a "decarbonized" economy more and more. Many "plans and strategies for developing and deploying hydrogen" have recently been developed with this goal in mind. Governments are initiating policies to facilitate the implementation of these plans by offering incentives for developing new delivery infrastructure and producing green hydrogen[4]. However, production costs are the primary obstacle to introducing and widespread use of green hydrogen. Creating green hydrogen requires significant water, like producing hydrogen through electrolysis powered by renewable sources. Therefore, water-related issues and essential geopolitical and economic ramifications of developing the hydrogen economy have been investigated and researched. Since the water crisis may affect the transition towards a green-hydrogen economy, innovators are employing electrochemical water electrolysis to produce hydrogen from two essential ingredients, electricity and water, to create a "green hydrogen economy" where emissions-free hydrogen will be widely used.

Some critics have started to wonder if there is enough water to support a hydrogen economy as the cost of renewable electricity declines and electrolyzer efficiency increases due to the apparent high water demand for the whole production process, including using water as a cooling agent and feedstock for thermoelectric methods of producing hydrogen, like steam methane reforming (SMR), some claim that the answer is no[5].

Hydrogen-Powered Transportation

Clean energy can be delivered and stored by hydrogen for various applications in the US economy, including transportation. It can drastically lower greenhouse gas emissions from vehicles such as trucks, buses, airplanes, and ships that contribute to air pollution. Transportation contributes to climate change by storing heat in the atmosphere, accounting for 29% of greenhouse gas emissions6. Hydrogen is a fuel and energy carrier that can power cars and trucks without emitting harmful emissions. Heavy-duty vehicles, which account for 5% of all cars on American roads, 20% of transportation emissions, and the majority of the country's mobile nitrogen-oxide emissions, can have their emissions reduced by hydrogen and fuel cells[6].

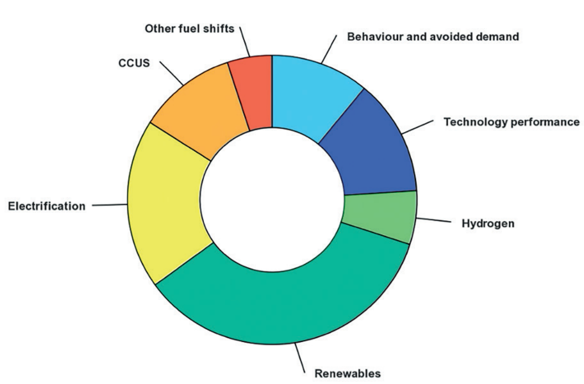

Figure 2: Cumulative emissions reduction by mitigation measure in the Net-Zero scenario, 2021-2050[6]

Batteries are found in some electric cars, while batteries and hydrogen fuel cells are found in other electric cars. Electric motors are found in every electric vehicle. Electricity directly charges the battery in electric vehicles that run solely on batteries. Hydrogen is kept in a tank and is used in cars with hydrogen fuel cells. After storing energy, the hydrogen enters a fuel cell and combines with atmospheric oxygen to produce electricity, which drives the electric motor. The advantages of using hydrogen fuel cell-powered vehicles are that they support zero carbon emissions, are quiet, efficient and support long distances with fast refueling. A car with a traditional combustion engine may be heavier and less effective. Hydrogen-powered cars use hydrogen fuel cells, which more effectively convert energy into electricity, instead of combustion engines. Fuel cells are two to three times more efficient than internal combustion engines at converting the chemical energy of fuels into electrical energy.

Fuel cells reduce vibrations from moving parts, which increases vehicle efficiency and decreases overall volume. Hydrogen fuel is perfect for fueling heavy-duty tractor-trailers and public transportation buses, as it enables vehicles to have longer travel times between tank refills. Public buses and drayage trucks, which are used to get goods from one place to another within the intermodal transport hub of a single freight

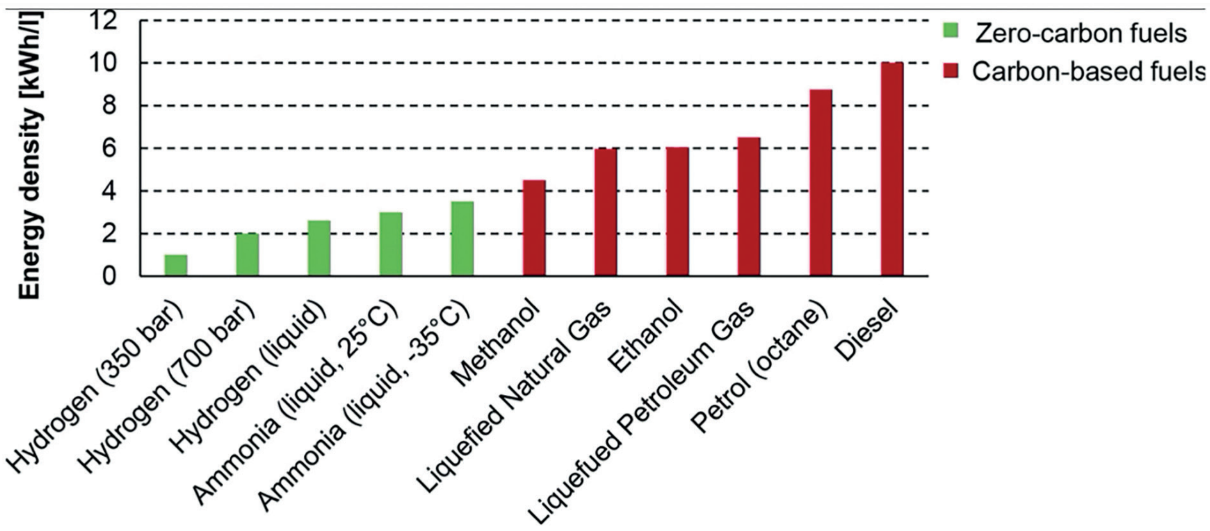

Figure 3: Volumetric energy density of a range of fuel options[10]

carrier and run on hydrogen fuel cells, are examples of zero-emission vehicles that can idle without causing air pollution. When their cars are stopped, drivers can continue to use the heating or cooling system to stay comfortable.

Current Status of Hydrogen Energy

According to an analysis by the International Energy Agency (IEA), using fuel-cell cars instead of diesel cars can reduce CO_2 emissions by 60%[7]. Additionally, they projected that by 2030, 2.4 million Fuel Cell Electric Vehicles (FCEVs) would be available on the transportation market, saving about 7% of CO_2 emissions[7]. As a result, nations worldwide are working to increase the availability of FCEVs. Germany and Norway want to supply 9000 FCEVs by 2025 in Europe with a 40% tax advantage over regular cars. Furthermore, several European nations run pilot programs for trucks and city buses[7]. The European Commission has established aggressive new CO_2 emissions standards for newly manufactured heavy-duty vehicles (HDVs) starting in 2030. With trucks, city buses and long-distance buses accounting for more than 6% of all greenhouse gas (GHG) emissions in the EU and more than 25% of GHG emissions from road transport, these targets will aid in reducing CO_2 emissions in the transportation sector. With these tightened emissions regulations, the road transportation industry could support the EU's zero-pollution and climate change goals and the transition to zero-emission mobility[8].

Government Support for Hydrogen Powered Vehicles

Denmark, Latvia, and the UK each receive 40 million euros from the Connecting Europe Facility to power 200 hydrogen fuel cell electric buses and related infrastructure[7]. In North America, the distribution of environmentally friendly automobiles is heavily advertised. For example, California offers subsidies of up to $11,700 per unit for medium- and large-sized cars and $5000 per unit for small- and medium-sized cars to increase FCEV supply[7]. Furthermore, pilot programs are being carried out with for-profit businesses to produce trucks and buses that run on fuel cells.

In Japan, the development of commercial vehicles, such as hydrogen city buses and trucks, is the primary focus of the Japanese council. They are trying to construct a transportation system powered by hydrogen by supplying 800,000 passenger cars and 1200 buses by 2030[7]. In China, a road map for the roll-out of hydrogen electric vehicles states that China aims to supply one million hydrogen-powered vehicles by 2030. In partnership with Ballard Incorporated, Chinese researchers are developing buses and trucks that run on hydrogen. Drones, ships, and hydrogen-powered trains are also in the development stage. In particular, Hyundai Motor Corporation has developed an idea called Urban Air Mobility, which links the sky and the ground to get around geographical and temporal limitations by creating key technologies, such as hydrogen technologies[7]. Here are some more examples of Hydrogen fuel cell vehicles in action:

1. Over 50,000 electric forklifts powered by hydrogen fuel cells are currently used nationwide[1]. Due to their low maintenance requirements and ability to be refueled quickly, these forklifts are being used by numerous large retailers across the nation to increase warehouse productivity.
2. California's most extensive public bus-only transit system is the Alameda-Contra Costa Transit District (AC Transit). Their Zero Emission Bus (ZEB) Program has grown from one hydrogen fuel-cell electric bus to a fleet of thirty-six forty-foot fuel-cell electric buses and a few battery-electric buses. The ZEB infrastructure of AC Transit consists of workforce training, on-site fleet maintenance, and on-site hydrogen production and fueling. By switching to zero-emission buses, they have avoided over 12,800 metric tons of CO_2 and generated over 5 million miles[1].

Advancements in Green Hydrogen Production

Though sustainable hydrogen production through biomass conversion and water electrolysis has advanced significantly, transportation and storage of hydrogen still pose significant obstacles to commercial-scale applications. Hydrogen regeneration can be achieved in an environmentally benign

Table 1: Detailed comparison between NH_3 and various commercial fuels based on energy density, heating values, and volumetric and energetic costs[11]

Type of fuel/storage	HHV (MJ kg^{-1})	Density ($kg\ m^{-3}$)	P (MPa)	Energy Density (GJ m^{-1})	Specific energetic cost ($ GJ^{-1})	Specific volumetric cost ($ m^{-3})
CNG (CH_4)/integrated storage system	55.5	188	25	10.4	38.3	400
Gasoline (C_8H_{28})/liquid tank	46.7	736	1	34.4	29.1	1000
Methanol	15.2	749	1	11.4	60.9	693
LPG	48.9	288	1.4	19	28.5	542
NH_3/metal amines	17.1	610	1	10.4	17.5	183
NH_3/pressurized tank	22.5	603	1	13.5	13.3	181
H_2/metal hydrides	142	25	1.4	3.5	35.2	125

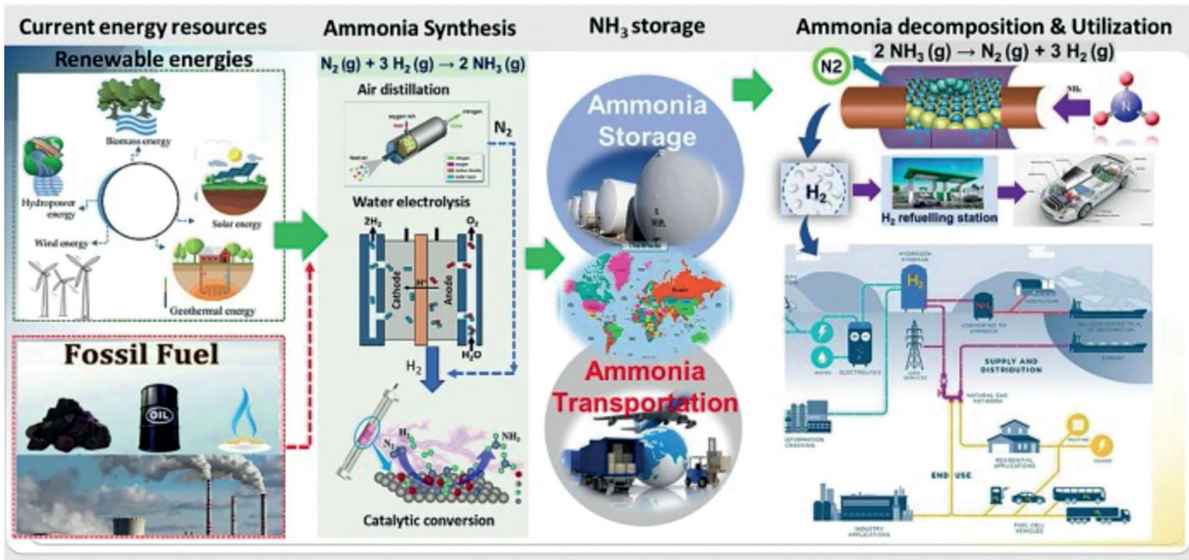

Figure 4: Key role of NH_3 as an energy carrier in current and future energy systems[11]

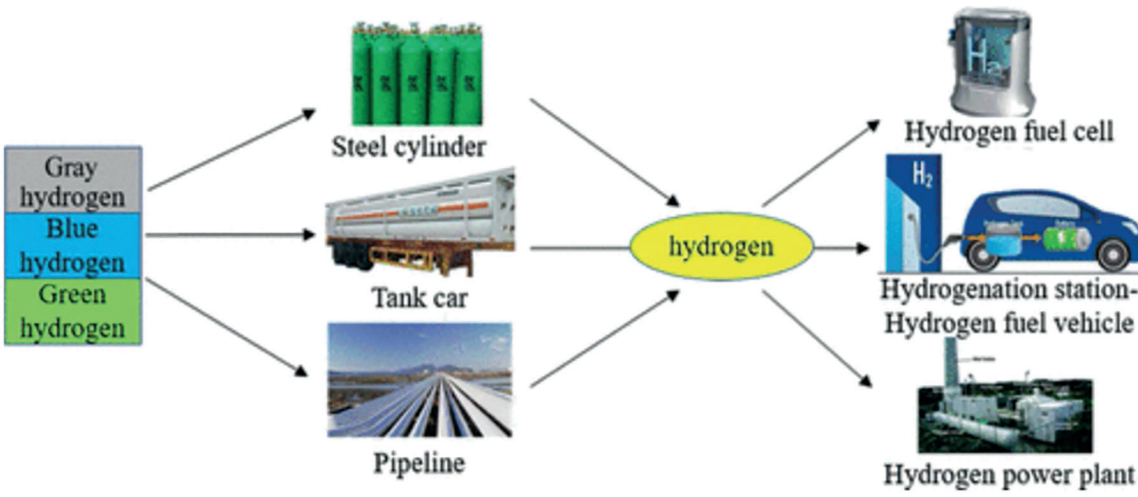

Figure 5: Overview of the Hydrogen industry chain[12]

way through catalytic cracking into nitrogen and hydrogen, as opposed to direct combustion of ammonia, which can produce nitrogen oxides[9]. Therefore, ammonia cracking can yield pure hydrogen as a clean fuel for developing futuristic and sustainable energy solutions. With a weight percentage of 17.8%, NH_3 has a high hydrogen content and can be liquefied at room temperature (33.34°C) under atmospheric pressure. Its storage and transportation are, therefore, reasonably simple[10].

Due to the remote locations of energy production and consumption sites, using renewable resources for electricity production results in intermittent and geographically imbalanced electricity production- a paramount task to researchers in meeting global demand. It is essential to design a new supply and demand system to address these temporal and spatial disparities[5]. Hydrogen-based energy carriers can realistically replace carbon-based fuels due to H2's high energy storage density (gravimetric density of 120 MJ Kg^{-1}) as a basis for such systems. Hydrogen's volumetric energy density (9.8 kJ/L) at standard temperature and pressure is significantly less than that of methanol (15.8 MJ/L) and gasoline (31.7 MJ/L), making it an infeasible long-distance energy carrier[11].

Nevertheless, carbon footprint reduction can only be achieved by developing sustainable technologies that use carbon-free energy carriers directly or indirectly. Ammonia can be used to store and transport hydrogen. Such benefits include ammonia being carbon-free, having a high volumetric energy density, mild liquefaction conditions (0.86 MPa at 20℃), and can be mass produced using the well-known Haber–Bosch (HB) process. The existing HB process heavily emits CO_2 and consumes much energy. Strategies have been developed to redesign the current technology by using water electrolysis for H2 production to achieve green NH_3 synthesis.

Ammonia decomposition has garnered considerable attention for H2 production, with a particular focus on understanding the reaction mechanism to maximize conversion and H2 production rates at the lowest possible reaction temperature[11]. Thermodynamically, NH_3 decomposition can reach 96.0–98.0% conversion at 300–350°C; however, most catalytic decomposition processes need a temperature higher than 450°C due to kinetic constraints[11]. Because of this, most of earlier research has concentrated on creating low-temperature decomposition catalysts by manipulating active metal type and particle size, support material, reactor assembly and adsorption binding energy.

The main economies of the globe have gradually turned their attention to hydrogen energy development because of its many benefits, including high efficiency, cleanliness, renewable energy and a wide range of other sources. The natural gas transportation pipeline network is comparatively complete and research is being conducted on developing the hydrogen pipeline transportation and storage system. A team has investigated the suitability of natural gas pipeline steel for high-pressure hydrogen environments. Hydrogen embrittlement in X80 pipeline steel is primarily caused by diffused hydrogen close to the steel's surface, as inferred from microscopic observations of tensile results at various pressures and strain rates. Several researchers have used the electrochemical hydrogen charging method to study various steel grades[12].

Liquid Hydrogen Storage and Transportation

High-pressure hydrogen gas storage and transportation, liquid hydrogen storage and transportation, and solid-state hydrogen storage and transportation are the three primary forms of hydrogen storage and transportation. Furthermore, a brand-new liquid storage and transportation approach has surfaced recently: liquid organic hydrogen carrier, or LOHC, transportation. LOHCs back the technological idea that the future of the green-hydrogen economy could function without requiring the handling of significant amounts of elemental hydrogen. Pairs of hydrogen-rich and hydrogen-lean organic compounds make up LOHC systems, which store hydrogen through recurrent cycles of catalytic hydrogenation and dehydrogenation. Utilizing the current fuel infrastructure is made possible by hydrogen handling in the form of LOHCs, which also enhances public trust in the handling of liquid energy carriers. Hydrogen release from LOHC systems yields pure hydrogen following condensation of the high-boiling carrier compounds, as opposed to hydrogen storage through hydrogenation of gases, such as CO_2 or N2[13].

The most popular current approach is high-pressure hydrogen gas storage and transportation. Hydrogen is transported to the destination in a sealed container or pipeline for pressure regulation after being pressurized to a specific pressure by a compressor at room temperature. High-pressure hydrogen gas is available at 15, 35, and 70 MPa. Specifically, 15 MPa hydrogen cylinders are well-established, 35 and 70 MPa hydrogen refueling stations are the central pressures at which hydrogen is currently stored and transported, and 70 MPa hydrogen storage and transportation is an area of intense research[12].

Another hydrogen storage technology that is gradually gaining traction among researchers is Solid-state hydrogen storage. With this technology, hydrogen is stored by reacting hydrogen with nonmetals, such as carbon nanotubes and activated carbon, rare-earth series, titanium series, zirconium series, and magnesium series- all known for their hydrogen-absorbing properties. Hydrogen is released via heating after its transport at room temperature and pressure. Solid-state hydrogen storage is even denser than liquid hydrogen storage, which is still undergoing experimentation. When hydrogen and water combine at specific pressures and temperatures, a crystal compound that resembles a cage is created. Particular hydrogen hydrates perform well in terms of hydrogen storage[12].

Fuelling the Future

The capacity of the green hydrogen market to lower emissions in buildings, power systems, transportation and industry proves its future potential. While maintaining the power system's flexibility, green hydrogen also has the potential to hasten the development of renewable energy sources. Green hydrogen also aids in long-term energy storage to counteract seasonal variations in energy. Most of the hydrogen produced today is gray hydrogen. It is relatively inexpensive and commonly used in the chemical industry to make fertilizer and refine oil. Unfortunately, almost 10 kg of carbon dioxide is released into the atmosphere for every 1 kg of gray hydrogen produced[14]. This high ratio of CO_2 generation gives this form of hydrogen its "gray" designation. Gray hydrogen is produced and used as an input by these industries, accounting for 17% of the 6.3 billion tonnes of carbon emissions released by industries worldwide[13]. Only green hydrogen derived from renewable energy sources can eliminate carbon emissions during production. Green hydrogen is currently priced between $5.5 and $9.5/kg, while gray and blue hydrogen is priced between $1.27 and $2.37/kg[13]. Green hydrogen is more expensive than gray and blue hydrogen. Due to recent drops in the cost of renewable energy sources and improvements in electrolyzer system efficiency, its price is expected to drop to less than $2.00 per kilo by 2030[13]. This price drop will inevitably create competition with blue and gray hydrogen via industrial applications among other industries.

With the use of hydrogen fuel cell systems, hydrogen may soon be used in heavy-duty vehicles like trucks and buses to lower emissions from the transportation sector. This is the market where it is anticipated that hydrogen and hydrogen fuel cells will be crucial in reducing emissions from the transportation sector.

In contrast to battery electric vehicles (BEVs), hydrogen FCEVs show many benefits, including the ability to travel farther and refuel much faster than BEVs. FCEV buses are already in practice in countries like Japan[13].

Low-carbon hydrogen has the potential to significantly cut emissions not only from moving automobiles but also from trains, ships, and airplanes. Acknowledging this potential, nations globally have progressively undertaken efforts to investigate and implement this kind of technology[13].

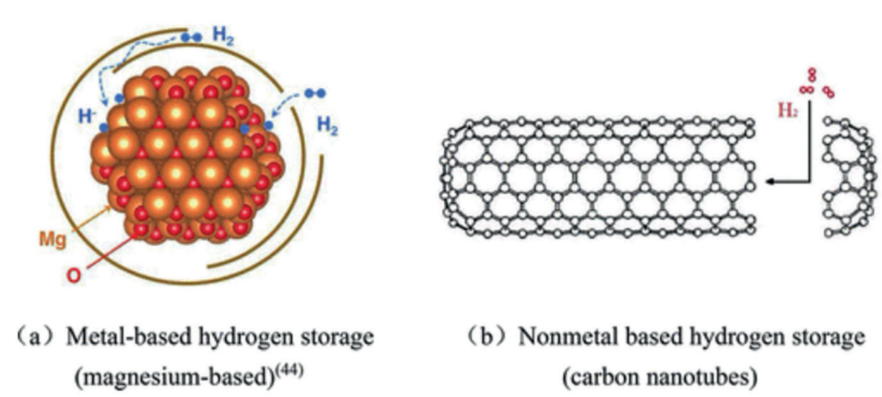

Figure 6: Diagram of solid-state Hydrogen storage[12]

Conclusion

One of the most promising ways to meet industry decarbonization targets, encourage the growth of renewable energy sources, boost system flexibility and guarantee national energy security is by producing green hydrogen from renewable energy. In addition to many advantages, using green hydrogen can significantly improve the environment compared to hydrogen derived from fossil fuels, which is currently the primary method of producing hydrogen. Due to the collaboration of numerous stakeholders, including enterprises, policymakers and research and development organizations, problems like the high cost of green hydrogen production compared to other production methods, the unpredictability of green hydrogen demand, and the impact of green hydrogen projects on land and water are being solved step by step. Governments have also developed hydrogen strategies for their nations to transition to a productive and long-lasting hydrogen economy[7]. Countries must begin implementing pilot projects as soon as possible to gain practical experience and capitalize on efficiencies through learning curves and scale effects on production equipment, such as electrolyzers. To achieve future greenhouse gas reduction targets, it is imperative to implement the necessary hydrogen infrastructure, which calls for developing projects now to ensure continuous demand growth8. Governments everywhere must work to develop laws that favor hydrogen and establish a regulatory environment that stimulates investment in production equipment.

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About the Authors

Dr. Raj Shah serves in the role of Director at Koehler Instrument Company in New York, boasting an impressive 28-year tenure with the organization. Recognized as a Fellow by eminent organizations such as IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute, and The Royal Society of Chemistry, he stands as a distinguished recipient of the ASTM Eagle award. Dr. Shah, a luminary in the field, recently coedited the highly acclaimed "Fuels and Lubricants Handbook," a bestseller that unravels industry insights. Explore the intricacies at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).

His academic journey includes a doctorate in Chemical Engineering from The Pennsylvania State University, complemented by the title of Fellow from The Chartered Management Institute, London. Dr. Shah holds the esteemed status of a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute, and a Chartered Engineer with the Engineering Council, UK. Recently honored as "Eminent Engineer" by Tau Beta Pi, the largest engineering society in the USA, Dr. Shah serves on the Advisory Board of Directors at Farmingdale University (Mechanical Technology), Auburn University (Tribology), SUNY Farmingdale (Engineering Management), and the State University of NY, Stony Brook (Chemical Engineering/Material Science and Engineering).

In tandem with his role as an Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Dr. Shah's impact spans over three decades in the energy industry, with a prolific portfolio of over 625 publications. Dive deeper into Dr. Raj Shah's journey at https://bit.ly/3QvfaLX.

For further correspondence, reach out to Dr. Shah at rshah@koehlerinstrument.com.

Ms. Salowa Siddique and **Mr. Nicholas Douglas** are part of a thriving internship program at Koehler Instrument company in Holtsville, and are students of Chemical Engineering at Stony Brook University, Long Island, NY where Dr. Shah is the current chair of the external advisory board of directors.

Salowa Siddique

Nicholas Douglas

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com