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The Emerging Hydrogen Economy

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By: Kelvin Mahal

As such, the renewables sector has focused on developing renewable and clean energy resources such as solar, wind, nuclear, hydropower and biofuels as alternatives to fossil fuels. However, hydrogen is set to make a return to the mainstream as the international community seeks to respond to the world's energy and climate challenges, particularly in light of the targets set by the 2015 Paris Climate Agreement and recent climate activism around the world.

What is the 'Hydrogen Economy'?

The term 'Hydrogen Economy' refers to the vision of using hydrogen as a clean, low-carbon energy resource to meet the world's energy needs, replacing traditional fossil fuels and forming a substantial part of a clean energy portfolio[2]. According to the Hydrogen Council, the international hydrogen market could be worth up to US$2.5 trillion by 2050, meeting 18 percent of global energy demand, providing 30 million jobs around the world and reducing carbon dioxide emissions by 6 gigatonnes per year[3].

There are several reasons hydrogen is again receiving serious consideration as an alternative energy source. In addition to a global desire for more environmentally friendly fuel sources, improvements in hydrogen technologies, increasing government support for climate-friendly fuel diversification (e.g., in countries such as Japan, Korea and Germany) and changes in global energy policy, in emission standards and in the global technology landscape (such as the rapid deployment of intermittent renewables that require grid-scale storage for system stability) all help to support the argument for developing the hydrogen economy. It is also generally recognized that hydrogen has the potential to decarbonize a range of industries.

A rising star of the renewable energy sector, hydrogen is a versatile and environmentally friendly resource which produces only pure water and heat when combusted. Although hydrogen has been traditionally used as a feedstock in several industrial processes (such as ammonia synthesis and the refining of crude oil), recent developments have shown that hydrogen can also be used for a number of applications, including electricity generation, transportation and storing energy from intermittent renewable sources.

How is Hydrogen Produced?

As hydrogen does not occur naturally in a pure form, it must be produced from other compounds such as oil, natural gas and water. There are various methods by which hydrogen can be produced, which are outlined in more detail below[4].

Natural Gas Reforming Process

At present, the majority of the world's hydrogen is produced through the natural gas reforming process, which involves using high-temperature steam to produce hydrogen from a methane source such as natural gas. This method is currently the cheapest and most efficient method by which hydrogen is produced and can be coupled with carbon capture and storage technology to reduce the carbon emissions produced in the hydrogen production process.

Gasification

Hydrogen can also be produced by means of 'gasification,' which is the process of, for example, releasing gaseous hydrogen compounds from coal or biomass utilizing high-temperature steam and oxygen in a pressurized gasifier. The resulting gas contains hydrogen, which is then reacted with steam to separate the hydrogen. This process can also be coupled with carbon capture and storage technology to reduce carbon emissions produced through the gasification process.

Renewable Liquid Reforming

Like with natural gas reforming/gasification, this process involves reacting renewable liquid fuels, such as ethanol, with high-temperature steam to produce hydrogen near the point of end use.

Electrolysis

Another commonly used method of producing hydrogen is electrolysis, which uses electricity to split water into hydrogen and oxygen. This method also provides the potential for establishing a zero-emission fuel chain if the electrolysis process is powered by renewable energy generated from solar or wind. In doing so, the process of both producing and then subsequently using hydrogen to generate energy would not produce any greenhouse emissions.

It should, however, be noted that, currently, the production of hydrogen from water requires the use of fresh water as the base material. The direct production of hydrogen from seawater requires the development of new technologies to achieve commercial viability. In geographies where fresh water is itself a precious commodity, the production of hydrogen requires a two-step process: (i) the production of fresh water by means of desalination technology, followed by (ii) the application of electrolysis for hydrogen production. Despite this additional step, the process has the benefit of being capable of implementation by utilizing existing and proven technologies.

Extraction from Ammonia

Ammonia is a colorless inorganic compound of nitrogen and hydrogen (NH_3), usually found in gaseous form with a pungent odor. Much research has been undertaken into finding methods of extracting hydrogen from ammonia, such as that undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. The CSIRO has created a metal membrane that filters out pure hydrogen gas from ammonia, which can then be used, for example, in fuel cell vehicles[5].

The advantages of extracting hydrogen from ammonia are that:

- Due to its chemical composition, the production of hydrogen from ammonia does not release greenhouse gas emissions.
- It is much easier to transport hydrogen in the form of ammonia that in a pure gaseous or liquid form (as will be discussed in greater detail below). If hydrogen can be produced from ammonia at the point of need (using, for example, the hydrogen membrane technology from CSIRO), it will be easier and cheaper to organize supply chains to support the use of hydrogen.

Extraction from liquid organic hydrides

Technologies for the extraction of hydrogen from liquid organic hydrides such as methylcyclohexane (MCH) are under consideration. MCH is produced from toluene and hydrogen, and both toluene and MCH exist in a liquid form at ambient temperatures and pressures. Hydrogen is removed from the MCH through a catalytic process, and the resulting toluene can be reused as the base for the production of MCH.

MCH is also capable of safe storage and transportation using existing technologies. However, at present there is no commercial scale project utilizing an MCH value chain.

Fermentation

Fermentation involves converting biomass into sugar-rich feedstocks that can then be fermented to produce hydrogen.

Potential Methods of Hydrogen Production

A number of hydrogen production methods are currently in development and are summarized below[6].

High-Temperature Water Splitting

This method aims to use high temperatures that are generated by sources such as solar concentrators or nuclear reactors to drive chemical reactions that split water to produce hydrogen.

Photobiological Water Splitting

This method intends to make microbes, such as green algae, consume water in the presence of sunlight to produce hydrogen as a byproduct.

Photoelectrochemical Water Splitting

Similar to high-temperature water splitting, photoelectrochemical water splitting aims to produce hydrogen from water using special semiconductors and energy from sunlight.

Uses of Hydrogen

Power Generation

A hydrogen fuel cell produces electricity by combining oxygen and hydrogen, with this combustion process generating electricity and producing only water and heat as byproducts. Small hydrogen fuel cells can power items such as laptops and cell phones, while at the other end of the spectrum, larger hydrogen fuel cells can provide electricity for powering buildings. As such, hydrogen has the ability to generate power on small, medium and large scales, which makes it a very attractive option for helping countries and corporations meet their decarbonizaton targets.

An example of hydrogen fuel cells being used as the sole energy resource to generate electricity for buildings is the three-story building at SP Group's training center in Singapore, the first 100 percent zero-emission building in Southeast Asia powered by green hydrogen. The building uses solar panels to generate power, which is then utilized in an electrolysis process to produce hydrogen. The hydrogen is then stored in tanks, where it bonds with metal alloy powders to form a metal hydride. When electricity is required, the stored hydrogen is then released and passed through on-site fuel cells to generate electricity. This hydrogen system was developed by SP Group in conjunction with Japan's Marubeni Corporation and Tohuku University[7] and the building is an example of how a zero-emission supply chain can be established when using hydrogen as an energy resource.

Moreover, several major power companies (including Mitsubishi Power Systems, General Electric, Siemens Energy and Ansaldo Energia) are developing gas turbines that can operate using a fuel containing a high volume of hydrogen[8], offering another method by which hydrogen can be used for power generation on a large commercial scale. MHPS (a joint venture between Mitsubishi Heavy Industries and Hitachi) and General Electric have been particularly focused on developing such turbines, testing natural gas containing hydrogen contents ranging from 30 percent to 90 percent. By blending hydrogen with natural gas, the carbon emissions created by the combustion process can be significantly reduced. For example, General Electric has found that using a 5 percent blend of hydrogen in the natural gas supply to a gas turbine can reduce annual carbon dioxide emissions by nearly 19,000 metric tons, using a 50 percent blend reduces carbon dioxide emissions by 281,000 metric tons and using a 95 percent blend reduces carbon dioxide emissions by 1.04 million metric tons[9]. Other companies are also undertaking research into hydrogen-only fired turbines.

Transport (Fuel Cells Electric Vehicles)

Many automobile companies, such as Hyundai, Toyota/Lexus, Honda and Mercedes-Benz, have undertaken substantial investment to develop hydrogen-powered vehicles, which possess both a longer range and much shorter refueling times when compared to electric vehicles. These vehicles are called 'Fuel Cell Electric Vehicles' (FCVs) and contain hydrogen fuel cells and hydrogen storage tanks that are capable of being refilled in a manner similar to cars fueled by gasoline.

Outside motor vehicles, hydrogen is already being used to power trains in both the United Kingdom and Germany and is also being tested as a fuel source for powering other modes of transportation, such as aircraft, ships and material handling vehicles such as forklifts and tow trucks[10], illustrating that hydrogen can power several modes of transport outside of normal automobiles and further demonstrating its decarbonizing potential and versatility.

It is also worth noting that many countries, particularly in Asia, have set ambitious targets to get more FCVs on their roads. China, the world's biggest automobile market with 28 million vehicles being sold annually, is aiming for more than 1 million FCVs to be in service in the country by 2030, compared with just the approximately 1,500 currently in use[11]. Japan, with sales of 5 million vehicles annually, is looking to have 800,000 FCVs sold by 2030, up from its current level of 3,400[12], and South Korea, whose automobile market is one-third the size of Japan, has set a target of selling 850,000 FCVs in the country in the same time frame, up from the current level of 3,000[13].

Hydrogen Energy Storage

Hydrogen Energy Storage (HES) is the process of storing energy in the form of hydrogen. Stored as hydrogen for use in fuel cells, for example, hydrogen is an alternative to battery storage. Intermittency, one of the key issues facing wind a solar power generation (i.e., the sun doesn't always shine nor the wind blow), can be resolved either by:

1. Using hydrogen fuel cells for power generation during periods when power cannot be produced from wind or solar.
2. Using wind and solar to produce hydrogen, e.g., from hydrolysis, and then utilizing the power per point 1 above.

Production of hydrogen utilizing wind and solar when coupled with hydrogen storage and transportation solutions (discussed further below) effectively also allows wind and solar energy to be “transported” in the form of hydrogen and converted back into electricity (for example, by fuel cell) when needed. The HES process can also be utilized to store energy from other renewable and non-renewable energy sources.

The hydrogen produced by the HES process is most commonly stored as compressed gas, but can also be stored as cryogenic liquid at very low temperatures, similar to liquefied natural gas (LNG). Other methods by which hydrogen can be stored include using metal hydride materials (referred to above) as well as various chemical hydrides[14].

The benefit of using HES is that it can address much longer storage timescales than batteries. For example, solid-state batteries are best suited to discharge times of four hours or less, while HES can address longer duration needs (days, weeks or longer) by simply adding more storage tanks or on-site hydrogen production similar to the SP Group building referred to above[15].

Recent Developments

Given its numerous uses and decarbonizing potential, countries and corporations around the world are intensifying their investment in hydrogen. In the United States, the funding provided by the U.S. Department of Energy for hydrogen and hydrogen fuel cells has ranged from approximately US$100 million to US$280 million per year over the last decade, with approximately US$150 million per year being invested in hydrogen by the U.S. Department of Energy since 2017[16]. Japan's Ministry of Economy, Trade and Industry has also budgeted hydrogen funding of approximately US$560 million for 2019[17], while China has also announced hydrogen transport industry investments of more than US$17 billion through to 2023.

Japan, one of the leading countries in hydrogen development, has set a goal of becoming the world's first 'Hydrogen Society,' which includes plans to build 900 hydrogen-refueling stations in the country by 2030[18]. Japan's energy ministry has also set ambitious goals in the lead up to next year's Olympic Games, intending to deploy 100 hydrogen fuel cell buses for the games (which is part of a longer term goal of deploying 200,000 such vehicles in the next six years[19]) and powering the Athlete's Village with hydrogen. In addition to the number of Japanese automobile companies that have been developing FCVs (such as Toyota, Honda and Lexus), a number of other Japanese companies have also invested heavily in hydrogen. For example, in March of 2018, a group of 11 Japanese companies (including JXTG Nippon Oil & Energy Corporation, Tokyo Gas Company and Iwatani Corporation) launched a venture called Japan

H2 Mobility, which aims to build 80 hydrogen fueling stations by 2022[20], with 12 stations already nearing completion.

Major Japanese power utility Electric Power Development Co., Ltd (known as "J-Power"), in conjunction with Kawasaki Heavy Industries, Marubeni Corporation, Iwatani Corporation and Sumitomo Corporation, and Australian Energy company AGL Ltd., with support from the Australian national and Victoria state governments, are building the world's first coal-to-hydrogen demonstration project. Located in Victoria, Australia, the approximately AUD$500 million project will produce hydrogen from the gasification of brown coal and then liquefy the hydrogen for shipment[21]. Akin Gump Strauss Hauer & Feld LLP is advising J-Power on its participation in this project. The project aims to demonstrate the technologies needed to potentially develop an integrated commercial-scale hydrogen supply chain that encompasses production, transportation and storage, with a goal of delivering liquefied hydrogen in a similar manner to LNG. The project is the first initiative proposing to transport mass quantities of hydrogen across open waters using an innovative liquefied hydrogen ship (which Kawasaki Heavy Industries is currently developing[22] with the first such ship being launched on 13 December[23]). When combined with geo-sequestration of unwanted gasses produced from the coal gasification process, the entire supply chain can effectively be greenhouse emission free.

Japanese company Chiyoda Corporation is also planning to demonstrate an international hydrogen supply route by importing up to 210 tons of hydrogen (enough to fill 40,000 FCVs) in a demonstration project in 2020[24].

IHI Corporation also announced in September of this year that it had started construction on a 1,000 square-meter hydrogen facility in Fukushima, which will focus on developing hydrogen carriers, including ammonia and methane, which can be used in the logistics steps of a hydrogen supply chain[25].

In Germany, hydrogen is now seen as an important option to fill the energy gap left from the impending closure of nuclear stations and the phase-out of coal-fired power. In 2019, the German government stated that it wanted the country to become "the number one in the world" for the technology and announced that 20 new research laboratories would receive a total of €100 million a year to test new hydrogen technologies for industrial-scale applications[26]. In addition, natural gas pipeline owners in Germany have asked the German government for rules that would allow them to carry more hydrogen in their pipelines. The world's first passenger train powered by hydrogen fuel cells, which can run for up to 1,000 kilometers on a tank of hydrogen and store excess energy produced by the fuel cell in on-board lithium-ion batteries, also began operating in Germany in September 2018[27].

Germany's biggest companies are also making substantial investments in hydrogen[28]. Siemens AG announced in July of 2019 that it was building a hydrogen laboratory system in eastern Germany, with German Chancellor Angela Merkel hailing the move as a "milestone." EON SE, a major utility company, is working on a project to blend hydrogen into natural gas grids at much higher rates than at present. RWE AG and Innogy SE are jointly evaluating a large-scale facility to produce green hydrogen close to Innogy SE's Westereems windfarm in the Netherlands. Meanwhile, Uniper SE has established a pioneering gas-to-power plant, which is the world's first facility to turn wind energy into a stored asset in the gas grid.

In the United Kingdom, the U.K. government has recently unveiled a £12 billion plan to use 4 gigawatts of offshore wind for renewable hydrogen production, which is scheduled to begin in the early 2030s[29]. Hydrogen interests in the U.K. have also attracted international investment, with The Linde Group recently investing £38 million for a 20 percent stake in London Stock Exchange-listed technology developer ITM Power[30]. London's Metropolitan Police Service has added 11 Toyota Mirai cars fitted with hydrogen fuel cells to its fleet of responsive vehicles, and in Scotland, a project which successfully used tidal power to produce hydrogen has been awarded €12 million in funding to develop a hydrogen power system for the car and passenger ferries that connect the Orkney archipelago[31].

In France, taxi company Hype, which currently has a fleet of 100 FCV taxis from Hyundai, is aiming to add a further 500 FCV taxis from Toyota by the end of 2020, with the company's ultimate goal being a completely zero-emission taxi industry in France by the 2024 Olympic Games[32]. France also deployed its first hydrogen-powered passenger bus in September 2019, and the Auvergne Rhône-Alpes region in France recently committed €200 million towards 1,000 hydrogen-powered vehicles and 15 electrolyzers[33].

In the U.S., the majority of investment in hydrogen has been focused in California, where there are currently 40 hydrogen-refueling stations and 7,000 FCVs in use (the U.S. already accounts for more than half of the world's FCVs on the road[34]). The California Fuel Cell Partnership (CFCP) aims to increase these numbers to 40,000 FCVs on its roads by 2022 and

200 hydrogen refueling stations by 2025[35]. In early 2019, the CFCP started work on building a large-scale liquid hydrogen production unit, with a capacity to produce nearly 30 tons of hydrogen per day, which will be able to fuel 35,000 FCVs. Moreover, Microsoft is studying how to use hydrogen fuel cells in their servers. General Electric has also installed over 70 gas turbines in the U.S. that previously have or currently are using various levels of hydrogen as part of the gas being used to power these turbines[36].

A coalition of major oil & gas, power, automotive, fuel cell and hydrogen companies have also come together to develop a "Road Map" to a U.S. hydrogen economy, detailing how the U.S. can expand its global energy leadership by scaling up its activity in the fast-evolving hydrogen industry[37]. Commenting on this road map, Morry Markowitz, President of the Fuel Cell and Hydrogen Energy Association, noted that in addition to hosting more than half of the world's FCVs, the U.S. also has more than 25,000 hydrogen fuel cell material handling vehicles, as well as more than 8,000 small-scale hydrogen fuel systems in 40 states and more than 550MW of large-scale hydrogen fuel cell power either installed or planned. Mr. Markowitz also noted that hydrogen could strengthen the U.S. economy by up to US$140 billion per year in revenue and generate 700,000 jobs by 2030, while by 2050, it is estimated that hydrogen will contribute US$750 billion to the U.S. economy per year, generate 3.4 million jobs and meet 14 percent of U.S. energy demand[38].

In Canada, Ballard Power Systems Inc., a hydrogen fuel cell company, has recently seen its shares climb significantly after 40 years of never posting a profit, with its stock being the best performing stock on the S&P/TSJ Index in 2019[39]. The reasons behind this rise are the introduction of more restrictive emission rules and stricter emissions targets across the world, which have occurred at the same time that the costs of both hydrogen and hydrogen fuel cells have fallen. The rise in Ballard Power's share price has also been attributed to an investment from a substantial Chinese investor, as well as rising speculation that there will be an upcoming mainstream adoption of hydrogen fuel cells[40].

Advantages of Using Hydrogen

Supply

As the third most abundant element on Earth, hydrogen can be found in resources including water, natural gas, coal and biomass, meaning that there is no possibility of running out of hydrogen, unlike fossil fuels, which are limited in their supply.

Decarbonization

The biggest advantage of using hydrogen as an energy resource is its ability to decarbonize a variety of industries, including the transportation and power generation industries. As detailed above, hydrogen fuel cells combine hydrogen with oxygen to produce energy, with the only byproducts of this process being water and heat. This makes hydrogen a very attractive alternative to fossil fuels, particularly given that if hydrogen is produced using energy from renewable resources (as explained above), then not only will industries be decarbonized, but the whole chain of producing and using hydrogen as an energy resource will be one that does not produce any harmful emissions or pollutants. As such, hydrogen possesses significant potential to assist with decarbonizing numerous industries and is, accordingly, an attractive renewables option for many countries and corporations around the globe.

Efficiency

Hydrogen is a very efficient energy resource, particularly in comparison to more traditional fossil fuels. For example, the traditional internal combustion engines operate at a very low efficiency level (approximately 25 percent), while, according to the Connecticut Hydrogen Fuel Cell Coalition, a stationary hydrogen fuel cell, when used with heating and power systems, can have an efficiency level that exceeds 80 percent[41].

Furthermore, hydrogen fuel is also more efficient than energy resources such as gasoline (a fuel cell coupled with an electric motor is two to three times more efficient than an internal combustion engine running on gasoline) and by weight contains more energy; for example, 1 kilogram (2.2 pounds) of hydrogen gas contains about the same amount of energy as 1 gallon (2.8 kilograms, 6.2 pounds) of gasoline[42]. In addition to the emissions-free nature of hydrogen use in FCV's, they can also achieve better fuel economy that vehicles using internal combustion engines. Also, while FCV and electric motor vehicles are not necessarily technological rivals (indeed, many see them as complementary), FCVs do have the advantage (based on present technology) of faster refueling and longer range (as FCVs can store additional hydrogen as fuel).

Powering Existing Renewables

The International Energy Agency (IEA) has noted that given hydrogen's capacity to act as a short- or long-term storage medium, hydrogen can assist with storing energy from intermittent sources such as renewables, storing this energy when demand is low and deploying it when required[43] (see the paragraph on 'Hydrogen Energy Storage' above). Moreover, the IEA has also noted that hydrogen (and hydrogen-based fuels) can transport energy from renewables over long distances, such as from regions with significant solar and wind resources in Australia or Latin America to cities thousands of kilometers away, enabling renewables to make an even greater contribution to the global energy mix[44].

Challenges Facing Hydrogen

Cost

While hydrogen is widely available, the cost of producing hydrogen is expensive given the time and energy required to separate hydrogen from other elements[45]. While the methods of producing hydrogen are becoming more cost-efficient, the cost of producing hydrogen remains high in comparison to other renewable energy resources and, in particular, fossil fuels. As such, the primary challenge for hydrogen production is to reduce the cost of producing hydrogen to make it competitive with other energy resources. This is particularly so when combined with the costs involved in storing and transporting hydrogen, as well as the costs of building the infrastructure required to support hydrogen as an energy resource on a commercial level, all of which are examined below.

However, it is important to note that the costs of producing, storing and transporting hydrogen as well as building the necessary infrastructure have been steadily decreasing. In addition, countries such as Japan have firm targets in place in order to try and make hydrogen more cost-competitive (for example, Japan has set a target for reducing the cost of hydrogen by one-third by 2030, from the current price of US$10 per kg (2.2 pounds) to US$3 per kg)[46]. There is also collaboration between the Japanese government and Japanese industry to help reduce prices for hydrogen fuel cells, which involves (i) extending its current fuel cell program to reduce the price of hydrogen and hydrogen fuel cells; (ii) beginning the large-scale introduction of hydrogen power generation and supply infrastructure; and (iii) establishing a zero-emission supply system throughout the manufacturing process[47]. The cost of producing energy from hydrogen fuel cells is also decreasing.

Storage and Transportation

One of hydrogen's properties is that it has a low density, meaning that it must be stored in a highly pressurized environment or in a liquefied state. Hydrogen must also be stored at low temperatures to ensure that is both efficient and effective as an energy resource. Furthermore, hydrogen needs to be transported in a highly pressurized or liquefied state at low temperatures, making it more expensive to move in comparison to fossil fuels such as oil and coal. Accordingly, at present, hydrogen is usually only transported in small quantities and requires specialized supply chains and logistical arrangements in order to make sure it is transported safely and effectively. The three main methods by which hydrogen is currently transported are[48]:

- **Pipeline**: This method involves using a pipeline to transport hydrogen, similar to pipelines that are used to transport oil and gas, and is the least expensive way to deliver large volumes of hydrogen.
- **High-Pressure Tube Trailers:** This method, which is generally expensive, involves transporting compressed hydrogen by truck, railcar, ship or barge in high-pressure tube trailers and is generally used for distances of 200 miles or less.
- **Liquefied Hydrogen Tankers:** This method involves cooling the hydrogen to a temperature where it becomes a liquid. While the liquefaction process is expensive, it enables hydrogen to be transported more efficiently (in comparison to using tube trailers) over long distances by truck, railcar, ship or barge.

Furthermore, while hydrogen has a high energy content by weight and is an efficient energy carrier, it does not have a high energy content by volume, presenting a particular challenge for storage[49]. Consequently, in order to store sufficient quantities of hydrogen gas, for example, it will need to be compressed and stored at high pressures, necessitating specialist pressure relief devices and equipment for both safety reasons and to ensure that the correct pressure is maintained.

As a result of these requirements, the costs of storing and transporting hydrogen remain high even though these have gradually been decreasing, particularly over recent years as investment in hydrogen has intensified. These high costs mean that, in comparison to the costs of storing and transporting other energy resources such as fossil fuels, storing and transporting hydrogen is still not currently deemed suitable for general commercial use from a cost perspective[50].

Infrastructure

A substantial amount of the energy infrastructure currently in place around the world is designed to support the use of fossil fuels, such as oil pipelines and coal power plants. As explained above, specialized equipment and infrastructure is required to transport and store hydrogen, let alone generate power.

While the infrastructure required to support the use of hydrogen is gradually being installed around the world, particularly in countries like Japan, it is not at a sufficient level to support the commercial use of hydrogen. For example, a commonly cited challenge to FCVs is a lack of refueling stations, which are costly to build (although it is also thought that a lack of refueling infrastructure is due to there being an insufficient number of FCVs on the road to make refueling stations profitable given their high cost[51]). When combined with the high costs of generating, storing and transporting hydrogen, it is unlikely that hydrogen will be able to rapidly replace lower-cost alternatives (such as gasoline).

A more cost-effective option may be to use or modify existing energy infrastructure (such as gas infrastructure) in order to transport and store large quantities of hydrogen, which is what German company FNB Posch has suggested should occur in Germany. The company is looking to carry a mandated share of renewable and decarbonated gases, including biomethane, synthetic methane and hydrogen, starting at a blend of 1 percent in 2021 and rising to 10 percent by 2030[52]. This would also help increase the uptake of hydrogen as an energy resource, fueling the growth of hydrogen, and will likely lead to a decrease in costs given that it would allow hydrogen to benefit from the economies of scale that would result from an increased uptake in hydrogen energy.

Uptake of Technology

Like with the infrastructure required to support hydrogen, the pace of the uptake of the technology required to support hydrogen as an energy resource has not been as fast as was initially hoped. For example, and as mentioned above, it is often said that the lack of refueling stations for FCVs is due to there being an insufficient number of FCVs on the road to justify building more refueling stations, which are themselves expensive. Moreover, the costs of hydrogen technology, although decreasing, remains high compared to more traditional sources (for example, a Toyota Mirai FCV costs US$46,200, which is about 50 percent more expensive than a Toyota Camry, which runs on a conventional gasoline engine)[53].

Furthermore, the uptake in the technology required to produce, store, transport and use hydrogen as an energy resource on both industrial and commercial scales has not been as fast as anticipated given the cost and complexities involved in building such infrastructure. In addition, there has been reluctance to invest in such infrastructure until there has been a wider uptake in hydrogen power, such as an increase in the number of FCVs on the road and/or the number of hydrogen fuel cells being used to generate power. As the costs associated with hydrogen continue to decrease, it is hoped that governments, corporations and individuals will begin to take up and install the technology required to support a hydrogen economy at a faster pace.

Safety and Environmental Concerns

One of the main challenges facing the vision of a hydrogen economy is the safety and environmental concerns that exist with regards to hydrogen given its properties and characteristics. Hydrogen is a highly flammable element that can cause explosions when leaked. This property of hydrogen can make it dangerous in enclosed areas such as underground tunnels or carparks. Hydrogen is also odorless and its flames are almost invisible to the naked eye, presenting challenges for both safety and detection[54]. Environmental concerns also arise with hydrogen, as current technology means hydrogen is generally made from fossil fuel reformation[55].

Advances in the technology used to generate energy from hydrogen as well as the implementation of strict standards and regulations regarding the use, transportation and storage of hydrogen have helped to reduce these risks and regulate the use of hydrogen so that it is used both safely and in an environmentally friendly manner. However, the perception regarding the environmental and safety problems associated with using hydrogen still persist and will need to be addressed in order for hydrogen to be used on a wide-scale and commercial level.

What Does the Future Hold for Hydrogen?

It is clear that hydrogen has the potential to form a substantial part of the global energy mix as countries and corporations strive to meet their climate change and decarbonization targets. The many applications and benefits of using hydrogen to generate energy make it particularly appealing and are core reasons governments and corporations globally are making substantial investments into hydrogen. Hydrogen's versatility and multiple applications, along with its ability reduce greenhouse emissions, increase energy security and support the deployment of renewable energy sources such as wind and solar make it very likely to play a significant part in the world's future energy mix.

While hydrogen faces various challenges (particularly as to the costs of its production, storage and transportation in addition to the infrastructure required to support its use as an energy resource), recent developments have shown that progress is being made on all of these, providing the foundation for hydrogen to become a widely used energy resource around the globe. Consequently, it appears that the outlook for the future of hydrogen as an energy resource remains promising.

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