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Large-Scale Green Hydrogen Storage and Transportation: Advancements and Challenges for Sustainable Energy Integration

Sunil Kumar Dewangan^{a*}, Assistant Professor

Divyang G Bohra^a, Assistant Professor

Krish J Suthar^a, Research Scholar

^aDepartment of Mechanical Engineering, Dharmsinh Desai University (DDU), Nadiad, India

* Correspondence: sunildewangan.mech@ddu.ac.in

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ABSTRACT

The transition from non-renewable energy sources to renewable energy sources is a significant step in the direction of a sustainable future. Hydrogen is acknowledged as a great renewable energy source, which may help overcome the energy intermittency challenges. Hydrogen must have convenient storage and transportation to become a green hydrogen, i.e., greenhouse gas emission-free energy carrier. Large-scale green hydrogen storage and transportation are pivotal for the effective integration of renewable energy sources within the current power grid infrastructure and may play the role of reservoir. The scalability of green hydrogen storage presents opportunities for terawatt-scale long-term energy storage, which is critical for decarbonization objectives and sustainable energy goals. This research thoroughly reviews the most recent large-scale green hydrogen storage and transportation technologies. It examines the various storage and transportation techniques, such as liquefaction, compression, chemical storage, solid-state storage, cryo-

adsorption, and hydrogen carriers, considering their benefits, drawbacks, most recent advancements, and economic factors. Findings reveal significant information on expenses, difficulties, and future developments in the field. Over time, technological developments and economies of scale should reduce the cost of storage and transportation, but in order to successfully commercialize new technologies, it is essential to solve issues with storage techniques, modes of transportation, efficiency optimization, and technology adoption. In-depth technical and financial analyses offer important insights for developing an economically and sustainably feasible green hydrogen sector.

KEYWORDS

Sustainable future, green hydrogen, decarbonization, storage and transportation technologies, economics.

1. Introduction

With hydrogen being an energy carrier rather than a primary energy source, storage and transportation will be crucial to its success. There is currently a large infrastructure built around the transport of natural gas, and methods to store hydrogen that have been developed for utilizing hydrogen in various industries. Storage and transportation methods are typically developed with cost effectiveness and safety in mind, however sustainability of these methods has been a minor concern as the hydrogen being stored or transported was not necessarily a green product. This essay reviews advancements and challenges in storing and transporting large scale green hydrogen with a focus on methods that will be sustainable long term solutions. (1)

Hydrogen is the most abundant element in the universe but is not naturally occurring in its molecular form and therefore must be synthesized from compounds that are abundant in nature. The use of green hydrogen generated from renewable energy sources (RES) such as solar and wind has grown significantly over the past decade as many countries aim to move towards a more sustainable energy solution. Hydrogen can be used to store energy from RES for long periods of time and facilitates energy sharing across nations. It has the potential to be used as a fuel for heating and transportation which are difficult to decarbonize, and as a reducing agent for various industries. However, the current production of hydrogen predominantly comes from fossil fuels and typically involves high greenhouse gas emissions. A significant increase in the use of hydrogen in its low greenhouse gas emission green form will be essential in achieving the European

Commission goals of reducing greenhouse gas emissions by 80-95% by 2050 and increasing the share of RES in energy to 55-75% by the same year. (2)

1.1. Background

An effective and efficient storage and transportation method must be developed and tailored for the emerging hydrogen energy industry. This paper is intended to identify advancements and existing methods of large-scale hydrogen storage and transportation. By identifying existing state-of-the-art methods, the potential weaknesses and strengths can be identified and provide a platform for the further development and improvement of large-scale hydrogen storage and transportation technologies. This thesis covers the various methods of hydrogen production and focuses on the various large-scale methods of hydrogen storage. It finishes off with the large-scale methods of hydrogen transportation. By identifying the weak points of the current technology, further development of large-scale hydrogen storage and transportation can be made. (3)

To date, hydrogen is intermittently stored and transported using conventional methods tailored from the natural gas and large petroleum industries. However, this method is not entirely suitable and sustainable. Due to the ease of technology transfer and cost efficiency, these methods have led to the practice of storing large quantities of hydrogen on metal hydrides and desorbing them in a controlled manner for transportation. (4)

In the modern world, with the rising energy demands and the depletion of natural resources, there is a call for sustainable energy to address the environmental problems. With the increase in development and use of renewable energy, the efficient means of storing and transporting energy to where it is intended to be used has become vital. Hydrogen energy is a potential and key energy carrier in the effort to build a clean and sustainable energy future. Hydrogen is versatile and can be used in various energy sectors. For example, it can be used in fuel cells to generate electricity or be burned to provide heat. Hydrogen can be produced from various domestic resources such as renewable energy and nuclear energy. Being the simplest and lightest element in the universe, hydrogen can combine with other elements, which means that hydrogen must be stored as a compressed gas or liquid. (5)

1.2. Purpose of the Study

Green hydrogen storage and transportation are essential components for the success of power-to-gas technology, an innovative pathway for renewable energy integration. Compared to storage of electricity in batteries, energy stored as hydrogen provides greater versatility in terms of storage capacity and potential for long-term storage. By converting electricity to hydrogen via water electrolysis, power-to-gas is a means of utilizing the existing natural gas infrastructure to store and transport renewable energy to end-use sectors. At present, the method of decomposing natural gas into hydrogen and solid carbon is the most cost-effective form of hydrogen production, but is not sustainable in the long run. With this in mind, our study will address the lack of advancements in sustainable green

hydrogen production and clarify the potential for renewable hydrogen to act as a store for surplus electrical energy. The focus of the study will be placed on the progress of water electrolysis technology and its efficiency in converting electrical energy to chemical energy, as well as methods to store and utilize the hydrogen in contributing to grid stability and providing energy to end-use sectors. (5)(6)

1.3. Scope

Moreover, transporting hydrogen in large quantities can also make it a viable energy carrier. This can be in the form of pipelines, underground tanks, or through ships. A comprehensive research is necessary to see the benefits and drawbacks of each type of transportation. As an example, pipelines are a common method of transporting oil and natural gas today. Building a hydrogen delivery infrastructure using the same principles and along some similar rights-of-way could capitalize on the existing pipeline technology. However, research will be needed in the future to determine the economy and safety of using pipelines. Changes in materials and construction methods may be needed to create a dedicated hydrogen pipeline infrastructure. This is clearly seen as an area rich for future work to move us that much closer to the hydrogen economy. (7)

The scope of this work revolves around understanding and deciphering various methods and ways in which hydrogen, whether currently or in the future, can be stored and then used as an energy carrier. This includes a significant amount of research in the area of storing hydrogen as it has the capability to change the whole energy industry. From storing in underground caverns to salt domes, to storing it on materials or chemically combining it so as to fulfill the energy needs when required. Simulation of various methods will give a comprehensive outlook as to what is the best possible way of storing hydrogen. (8)

2. Green Hydrogen Production Technologies

Electrolysis of water is a simple process that can be accomplished in a number of different ways, but the basic idea is to separate the oxygen and hydrogen in water, which can be used as hydrogen gas, using an electrical current. Biomass gasification has the potential to produce hydrogen with minimal byproducts and could be coupled with carbon sequestration. 'Green' gasification involves using agricultural, forestry and waste biomass, which does not contribute to net carbon emissions. The gasification process itself is versatile and can be used to produce hydrogen as an energy carrier or for ammonia production. Thermal high-temperature processes using fossil fuels to provide the heat are also capable of producing large amounts of hydrogen, but are not considered 'green' unless the resulting CO₂ is captured and also weather thermal processes using energy from renewable sources. The end result for any thermochemical process is the separation of hydrogen from oxygen in water, using the thermochemical process to achieve this defines the different methods. (9)

2.1. Electrolysis

Electrolysis is the most commonly used method for water splitting. In principle, the electrolysis of water involves the use of two electrodes placed in the water and applying an electrical current which will cause the water to decompose into its gaseous components. The two electrodes are simply connected to positive and negative terminals of a source of direct current. The electrode at which the negative terminal is connected dissolves oxygen from the water and forms hydrogen gas at the surface, while the electrode connected to the positive terminal dissolves twice the amount of oxygen and forms H₂O. Carryover of the electrolyte material is of course a primary concern, as this would prevent the storage and transportation of green hydrogen. There are four recognized methods for carrying out electrolysis, these being alkaline, polymer electrolyte membrane (PEM), solid oxide and enzymatic. Alkaline electrolysis has been a tested technology for around 75 years as of 2020 and is the cheapest most proven method in industry. However as renewables have become a main driver in electrolysis R&D, there is a general consensus that alkaline electrolysis technology is geared towards sustaining current hydrogen volumes through reformation of natural gas, rather than producing sustainable hydrogen with renewable energy. There is a lack of reliable data concerning enzymatic electrolysis and only just over a decade of research into this method. Due to this it is difficult to measure potential for development, although the use of enzymes to catalyze electrodes poses a potentially low cost and efficient method for sustainable hydrogen production. Currently the most developed and widely reviewed method, PEM electrolysis is seeing ever increasing research as it becomes the most attributed electrolysis method for production of hydrogen from renewable resources. This is due to its ability to be easily coupled with variable renewable electricity during off peak periods, shut down completely and have a near instant response time to full capacity with minimal energy loss through part load efficiency. This compares particularly well to alkaline electrolysis which has a low partial load efficiency and is not easily degraded and restarted. A recent life cycle assessment has estimated PEM electrolysis to produce hydrogen from wind energy with a GHG emission of 2.94 gCO₂-eq/kWh, compared to steam methane reformation producing hydrogen with a GHG emission of 9.39-9.57 gCO₂-eq/kWh. With significant improvement and cost reduction, PEM electrolysis will be a strong method in developing a renewable hydrogen economy for sustainable energy integration. High temperature solid oxide electrolysis cells (SOEC) boast higher efficiency than their solid oxide fuel cell (SOFC) counterparts, as they operate in an electrolysis mode at upwards of 80% electrical efficiency and a round trip energy efficiency (electrolysis of hydrogen and oxygen and subsequent synthesis to water) at 63%. SOEC on its own will offer a lower cost hydrogen compared to current steam methane reformation when using renewable heat sources. However the most definitive advancement in this technology is reversible operation with renewable electricity, enabling grid load balancing with hydrogen production and very high efficiency off peak hydrogen storage. This is a technology perhaps in its early stages but with great potential, providing a means

for renewable hydrogen to effectively compete with gas products on cost, while offering a variety of microgrid and grid support services. (10)

2.2. Biomass Gasification

Biomass gasification is a promising route for the production of hydrogen. The global interest in the use of biomass or bio-derived resources for energy and fuel production has increased dramatically during the last decade. One of the most interesting options is the production of hydrogen, which is seen as a future energy carrier by utilizing the gasification of different carbonaceous materials. Hydrogen production by gasification is an attractive route due to the process flexibility to use various forms of feedstocks and the ability to handle relatively high sulfur and ash contents in the feedstock. Gasification-derived syngas can be utilized in the production of clean liquid and gaseous fuels as well as chemicals. As the use of hydrogen as an energy carrier or industrial feedstock increases, there may be interest in direct production of hydrogen from gasification in a cost-effective and efficient manner.

In gasification, the biomass solid reacts with oxygen and/or steam to produce syngas. The syngas can then be used for hydrogen production by a shift reaction and then followed by a water gas shift reaction to produce a high-purity hydrogen product. Execution of an auto-thermal gasification process, which can self-internally produce heat from the gasification reactions through limited oxidant, will combine the gasification and shift reaction processes into a single step allowing for an efficient hydrogen production process. (11)

2.3. Thermochemical Water Splitting

The United States Department of Energy has set a goal for hydrogen to make up 5-10% of the American energy market in the near future. The most efficient way to produce hydrogen is through a technique called "thermochemical water splitting." It is estimated that this process can produce hydrogen efficiently at a cost of approximately \$2.00/kg which is the DOE's stated price to make hydrogen a competitive energy source. There are two major steps in the process which are high temperature steam electrolysis and Iodine-Sulfur (I-S) thermochemical cycle. The high temperature electrolysis process can utilize electricity from nuclear power to provide heat which in turn heats steam to release hydrogen and oxygen. The I-S process operates at an optimal temperature of 850-950 degrees Celsius, which seems quite redundant to the high temperature electrolysis process. Using the waste heat from a nuclear power plant to drive the I-S process would indeed provide an efficient means of hydrogen production. (12)

3. Large Scale Hydrogen Storage Methods

Salt caverns offer the cheapest subterranean storage method because they are relatively inexpensive to produce and have the least amount of regulatory barriers. They are constructed by leaching out a cavern in a salt formation, and due to plastic flow that salt formations exhibit, the caverns exhibit high integrity, with a very low likelihood of fracture that would cause a leak. The storage of hydrogen occurs by injecting the gas into the cavern,

and due to the fact that the cavern is not backfilled, stored gaseous and liquid hydrogen can be removed. The drawback of salt caverns is that they are only found in specific geological environments, meaning they are not accessible to all. This method is only suitable for large-scale storage due to the size and cost of the caverns and is the only subterranean storage method that has been demonstrated to date for hydrogen, with the largest demonstration being a $2.6 \times 10^6 \text{ m}^3$ hydrogen storage facility in Teeside, UK. Simulation studies have shown that salt caverns offer a high efficiency and low-cost method of hydrogen storage. (13)

3.1 Underground Salt Caverns

The general process of hydrogen storage in any of these forms includes production, pressurization, transport, delivery, and use in stationary and mobile applications. The roundtrip efficiency of a storage method is the energy that is able to be utilized when the electrical energy used for hydrogen production and the energy losses in the storage, transport, and delivery steps are considered. It is important to differentiate hydrogen storage and the storing of any other fuel, as hydrogen has the highest specific energy by weight making it an excellent energy carrier, but the lowest specific energy by volume which makes storage more challenging than any other fuel. Therefore, the goal of a storage system is to store and utilize the hydrogen in the smallest volume possible while still being cost-effective, safe, environmentally friendly, and energy efficient.

3.1. Underground Salt Caverns

Underground caverns are large, naturally occurring cavities or man-made mines. Of particular interest to the energy industry is salt caverns. Salt caverns can be an economic, secure, and environmentally benign method for storing large amounts of hydrogen. They are generally formed by drilling a well into a salt deposit, then using water to dissolve the salt and create a cavern. The water is then pumped out, and the cavern is left to dry before any hydrogen is introduced. Leakage tests on salt caverns have shown very low permeability to be expected from the surrounding salt. This is an advantage over porous rock materials where hydrogen can be lost through relatively high permeabilities in the event of an unanticipated release, resulting in a build-up in pressure. Due to the low density of hydrogen, caverns can store large amounts of hydrogen, requiring a smaller footprint than above-ground tank storage. This may be important for installations that are size-limited or for land where there is a high opportunity cost for its use. Offshore salt caverns may also be a viable option for maritime energy transportation and storage. (13)

3.2. Liquid Organic Hydrogen Carriers

The third method is termed the Liquid Organic Hydrogen Carrier (LOHC) method. This concept is based around using organic compounds that can soak up hydrogen through reversible hydrogenation reactions. Once the hydrogen is bonded to the compound, the whole thing acts as a liquid hydrogen storage medium. The advantage of the LOHC method

is that the compounds can be used in existing infrastructure as a direct replacement for oil products as they are also liquids at room temperature. Recent investigations of LOHC material have identified nitrogen heterocycles such as carbazole, tetrahydroquinoline, and quinoline as candidates for a hydrogen storage medium. These compounds have the ability to store up to 6.7 wt% of hydrogen with little energy loss in hydrogenation/dehydrogenation reactions. LOHCs release hydrogen through heating, and the study of hydrogen release via catalytic dehydrogenation of hydrogenated nitrogen heterocycles may offer a method of controlling the rate of hydrogen release according to demand. The dehydrogenation process for nitrogen heterocycles forms an intermediate of an aromatic amine, and this conversion has the potential of being a highly effective and reversible hydrogen storage process. Finally, after hydrogen is released, the LOHC can be recycled to remove any spent amine from the hydrogen storage equilibrium, and fresh hydrogenation catalysts can be added to remove or degraded material to return it to a hydrogenated state. (14)

3.3. Metal Hydrides

Metal hydrides hydrogen storage method has garnered much attention in the scientific community because of the fact that the bonds between hydrogen and the metal atoms are relatively stronger compared to other materials at normal conditions. The basic concept behind metal hydrides is that the metal of the alloy (mostly rare earth, alkali, or alkaline earth metal) absorbs the hydrogen and forms a solid solution. When the pressure and/or temperature is increased, the hydrogen occupancies in the interstitial sites are increased and the solid solution is transformed into metal hydrides. This absorption is a reversible reaction, and hydrogen can be desorbed by a reversible process. The advantages of metal hydrides hydrogen storage include the absence of electrolysis and oxygen in the process. Metal hydrides can store hydrogen to a very high storage density compared to the gaseous storage method, and they require a minimal amount of compression. The storage is completely contained within pressure vessels, maintaining simplicity in design. Metal hydrides storage systems are reported to be very safe because desorption of hydrogen only occurs at elevated temperature and pressure, and because hydrogen is absorbed into a solid-state solution, there is a very low potential for leakage even in the event of a pressure vessel failure. (15)

3.4. Compressed Hydrogen Gas

Currently, compressed hydrogen storage is performed at ambient temperature in steel storage tanks at pressures ranging from 200 to 400 bar. In order to meet the DOE 2015 system level target of 6 wt% hydrogen on a total storage system weight basis, the storage vessel should contribute less than 12 kg in additional weight to store 100 kg of hydrogen. Using the 6 wt% target and assuming a 350 bar storage pressure, the energy density requirement for the hydrogen storage system can be computed to be 12.6 kWh/kg. (This is a system level calculation including the weight of the compressed hydrogen and the weight

of the storage tank.) With current compression and tank technology, achieving this energy density is possible, but is likely to be expensive. Most of the cost is associated with the compression and cooling power. The energy associated with compressing 100 kg of hydrogen from 1 to 350 bar is 8.4 kWh. Compression from 350 to 700 bar (a possible future storage upgrade) requires an additional 4.4 kWh. Energy required for compression cooling is approximately 7 kWh. Thus a total of approximately 20 kWh of compression and cooling power is required to store 100 kg of hydrogen at 6 wt% in a 700 bar tank. Since compression and cooling can be expected to cost approximately 15% of the total power consumed, the cost of high pressure hydrogen storage can be approximated to be 3 kWh. (16)

The previous three sections described hydrogen storage technologies that are in a relatively early stage of development and are targeting niche energy problems. In contrast, compressed hydrogen gas storage is a mature technology used routinely in various industries. The basic physical and thermodynamic principles that determine the energy requirements for compressing and decompressing H₂ are well understood. The current and projected future performance of well established materials of construction such as high strength steel are also well known.

4. Transportation of Green Hydrogen

Interest in the large-scale green hydrogen storage and transportation: advancements and challenges for sustainable energy integration throughout the present world has provoked this essay aimed at presenting the primary methodologies that are currently being investigated to transport clean hydrogen from where it is conveyed to where it is used. Since the ambition is fundamentally to replace fossil fuels, the mode of transportation must be competitive with the systems used for oil and gas. The intention is to enable the hydrogen to be transported cost-effectively to remote locations or in large quantities. To be productive, any approach ought to be capable of conveying hydrogen at a rate of a few million standard cubic meters each day (Nm³/day). Transport systems can be categorized into four general classes: trucks, trains, barges, and ships; pipelines; and by wire (i.e. transmitting power and making the hydrogen at the desired destination). While the latter is the most efficient means of transportation, this is not always attainable. The first three will be the focus of this essay with the majority of consideration given to pipeline transportation.

The most basic method for transporting hydrogen is by truck. Hydrogen container trucks are now being used all over the world, typically to convey hydrogen from the point of production to the closest point of use. This strategy is practical and financially manageable for small quantities of hydrogen. Depending on the begetting, hydrogen can likewise be compressed and stored in liquid form (LH₂) which is the most densely constrained energy storage media. An ordinary truck trailer can convey around 7000 gallons of LH₂, measuring around 570000 SCM (standard cubic meters). Liquid hydrogen trucks are

generally designed with an insulated semi-trailer and a self-contained refrigeration system. Because hydrogen is the smallest and lightest atom, it can without a very remarkable stretch escape by embrittlement any materials which it is contained. This makes the management of hydrogen very problematic as it will cause a loss of pressure and stacked up an exorbitant maintenance due to material weakening. The truck should thus have an unequivocally confirmed system, which may be insufficient and require constant checking for leaks. Safety is a huge concern, as hydrogen is a highly flammable and reactive component. Any release of hydrogen during transportation can prompt a danger of fire or an explosion. Notwithstanding these concerns, LH2 trucks are compelling and safe enough to be the primary means for transporting hydrogen to a larger scope in countries that produce the hydrogen in distant locations e.g. Japan and the U.S. Viable developments in materials and further development of safety codes could serve to further develop the present situation for LH2 truck transport. (17)

4.1. Pipeline Infrastructure

New pipelines dedicated to hydrogen can be built if there is a large demand for hydrogen fuel. One example of a large hydrogen pipeline project is the Dakota Minnesota and Eastern Railroad (DM&E) project, which would link the western and eastern power grids of the United States with a 750-mile hydrogen pipeline. Hydrogen pipelines can be built using many of the same techniques used in natural gas pipeline construction, and can be cost-effective in areas where large local demand for hydrogen exists. However, the cost of building a hydrogen pipeline can become prohibitive if the demand is not large enough or if the pipeline must cross large bodies of water or other impassable terrain. In cases where there is a demand for hydrogen but no cost-effective way to build a pipeline, transportation of hydrogen by truck or rail may be a more feasible option. (18)

The use of existing natural gas pipelines for transport of hydrogen is possible, since hydrogen has been conveyed in some of these pipelines in various test programs and demonstrations. Since hydrogen causes a phenomenon known as hydrogen embrittlement in many metals, there are concerns about using existing natural gas (methane) pipelines to transport hydrogen. Hydrogen embrittlement makes the metal in the pipeline more susceptible to cracks and failures, which can ultimately lead to the escape of hydrogen at high pressure.

4.2. Liquid Hydrogen Tankers

The large-scale supply of liquid hydrogen presents a competitive solution to the transportation and distribution of hydrogen. The current investment in liquid hydrogen supply has been reflected by the steady progress in the development and demonstration of liquid hydrogen tanker trucks. Tanker transport has acquired a favorable and reliable track record for delivering liquid hydrogen over both short and long distances. Since the late 1990s, progress has been made in the development of prototype liquid hydrogen tankers and their over-the-road demonstration in the US and several European countries. The major

accomplishments have been the successful over-the-road demonstrations of prototype liquid hydrogen tankers at the 150-250 liter capacity range. After successful demonstrations at this capacity, the next phase of development is the design and assembly of liquid hydrogen tanker trucks with increased capacity. The target goals for liquid hydrogen tankers are the development and demonstration of trucks with 1000 liter capacity (7-10 day supply for a typical user) and ultimate development of cryogenic tanker trucks carrying 5000-10000 liters of liquid hydrogen. Subscale liquid hydrogen tanker truck tests have been conducted at the Otay Mesa hydrogen station (San Diego, CA) in preparation for a full-scale demonstration in California. These tankers have previously been used in commercialization projects transporting liquid hydrogen to and from industrial sites (fuel cell and aerospace applications) and LH2 fueling stations in the Los Angeles, CA and Hartford, CT areas. (19)

4.3. High-Pressure Tube Trailers

In this sophisticated method of transporting hydrogen, the gas is compressed to high pressures, up to 20,000 psi, and stored in tube trailers. The tube trailers are similar to compressed natural gas (CNG) tube trailers and consist of a series of hydrogen storage tubes stacked on a pallet. The pallet is then loaded onto a truck or a train and transported to the site of delivery. Currently, tube trailers are the most flexible means of transporting hydrogen, as they can go anywhere there is a road or railway and can deliver hydrogen to places without an off-loading facility. The tube trailer can simply be unloaded at the site and picked up when it is empty. This method of transportation can be an effective way of delivering hydrogen to the initial refuelling stations of a hydrogen infrastructure as it eliminates the need to construct an offloading facility if there is no infrastructure already in place. However, the cost of tube trailer transportation is quite high. Studies of hydrogen fuelling stations show that hydrogen delivered by tube trailer can cost 25-155% more than hydrogen delivered by pipeline depending on the quantity of hydrogen delivered. This is due to the high cost of high-pressure storage and transportation and the efficiency of scale in pipeline delivery. High-pressure tube trailers allow for a high quantity of hydrogen to be delivered in a small package, but the compression and decompression of the hydrogen are less efficient than with large-scale industrial pipelines. In addition, the high-pressure storage used for tube trailers is the most expensive form of compressed hydrogen storage, making tube trailers less economical than other forms of transportation and delivery. (16)(20)

5. Integration of Green Hydrogen in the Energy Sector

Hydrogen is an energy carrier that requires its own production and conversion technologies, and its widespread use is contingent on cost effective ways to produce and supply hydrogen whilst reducing emissions. Power generation with hydrogen as an alternative to fossil fuels has been a particular focus given the possibilities to utilize hydrogen in high efficiency, low emissions power generation processes, and directly

connect renewable energy sources with a grid-based energy supply. The latter is possible if hydrogen production via water electrolysis can be matched with electricity production from renewable sources. By utilizing hydrogen with power generation technologies such as fuel cells and combined cycle turbines, it is possible to achieve virtually emission-free electricity generation. High efficiency production of hydrogen and electricity with fuel cells and the ability to utilize existing turbine technology both represent near-term commercial opportunities. The longer-term prospect of providing base load electricity from renewables via hydrogen and fuel cells offers a long-run sustainable alternative to fossil fuels and a way to mitigate the intermittency of renewable power sources. Overall, power generation represents a key entry point for hydrogen into the energy sector and a means to increase renewable energy utilization. (21)

5.1. Power Generation

The production of hydrogen through water electrolysis using renewable energy resources presents an opportunity to align the power and transport sectors. Hydrogen has potential use as an energy storage medium and energy carrier for sectors with otherwise limited opportunities to utilize low cost, low emissions energy. Hydrogen may be used to facilitate increased utilization of renewables in the electricity generation sector, to decarbonize energy use in industry, including feedstock and heat provision, and as a clean burning fuel for transport. These opportunities exist to help increase the proportion of energy consumption drawn from renewable resources and decrease reliance on fossil fuels. Each of these sectors is discussed in the following sections.

5.1. Power Generation

In the longer term, if advanced nuclear power plants featuring good load following capability and hydrogen production via thermochemical water splitting become widespread, it may be possible to use this hydrogen in a future advanced version of a gas turbine-based plant. However, this would likely require a very extended period of R&D and development as well as a large increase in nuclear capacity.

For new power plants, one of the more promising options is to use hydrogen in an Integrated Gasification Combined Cycle (IGCC). In this process, the hydrogen is used to fuel a combined cycle plant, which has a gas turbine and a steam turbine, but it is the method by which the hydrogen is turned into electricity that offers superior efficiency and lower emissions compared to a simple cycle plant. During the gasification process, coal is reacted with oxygen and steam to produce a hydrogen-rich gas. This gas is then purified and used as a fuel in the gas turbine to produce electricity. The heat from the gas turbine is then used to produce steam from water, which is used to fuel a steam turbine. By using this process with hydrogen as the fuel source, it is possible to obtain an efficiency of around 42% HHV, compared to around 35% HHV for a conventional coal plant. In addition to this, because the only combustion process involved is with the gas turbine, which produces

very low NO_x emissions, and the fact that the gasification process itself can be designed to include Carbon Capture and Storage, this method offers a much cleaner method of electricity production from coal. This will be particularly important in a future scenario where there are widespread carbon constraints, as it can allow continued use of the vast available coal resources in a far cleaner manner. High temperature steam electrolysis with very high temperature gas cooled reactors or using chemical looping (using oxygen for gasification and heat production in a loop with a metal oxide) are also possible future options for gasification. (22)(23)

The hydrogen can be applied in a number of different ways to improve the efficiency and environmental performance of power generation. Due to the versatility of hydrogen, which can be used in fuel cells for electricity production or in gas turbines for combined electricity and heat production, there are many different possible applications, both for new and existing power plants. This section considers some of the more near term and longer term hydrogen applications in power generation.

5.2. Industrial Applications

A number of glass producers in Europe, Japan, and the USA, and aluminum producers in Canada use hydroelectricity. This often is not a sustainable practice as usage of electricity is constrained by further hydro development and these industries can contribute to load balancing problems with too much inflexible power. These are good opportunities for these industries to utilize renewable or low-carbon hydrogen through off-peak electrolysis and fuel cells for onsite power or heat generation. An example would be existing polymer electrolyte fuel cell cogeneration systems in Japan used for homes that could be upscaled for large commercial use in the future.

Fuel switching is the simplest mode of harnessing hydrogen for industry. It involves substituting hydrogen for natural gas and other hydrocarbon fuel inputs to provide high-temperature heat in thermal processes, such as glass, steel, and aluminum production, or in fuel cells. Many glass and metallurgical industries globally are quite competitive and are widely dispersed in markets where there are great concerns to reduce local emissions. This means they are under increasing pressure to install best energy-efficient and clean technology practices.

The industrial sector is the largest consumer of chemical energy sources in the form of both electricity and fuels. Because of this, industrial applications have been widely hailed as the most immediate and biggest market for hydrogen technologies. In the short to medium term, increases in the cost-effective and efficient use of hydrogen in fuel switching and for the longer term, use of hydrogen in new integrated hydrogen-based processes have good potential. (24)

5.3. Transportation Sector

Green hydrogen is a promising and clean energy carrier for various transportation systems ranging from small vehicles to large ships. Power to hydrogen could be the best renewable option for powering fuel cell electric vehicles (green hydrogen) relative to plug-in batteries if high renewable electricity penetration can be coordinated into the time that electricity prices are lowest. Green hydrogen would also be the best option for meeting the International Maritime Organisation's vision of eliminating harmful emissions from shipping. Hydrogen fuel would also be suitable for aircraft and freight trains which rely on energy-dense fuel with minimal refuelling downtime. Sustainability in hydrogen production must still be maintained with hydrogen used in transportation. If it is produced, as many current industrial sources are, using fossil fuel with CO₂ emissions, it is not a clean energy carrier. With a coordinated effort to implement renewable sources of hydrogen production, there is potential to preserve our environment while meeting all societal energy needs. Hydrogen has been suggested as an energy carrier for a more sustainable future that can meet increasing energy demands and also lower greenhouse gas emissions. This is due to its efficiency, high energy density, and the potential for zero emissions. In present day, the majority of hydrogen is produced as a pure end product at refineries and is an important feedstock for various industrial processes. This is labeled as grey hydrogen and is an unsustainable method of hydrogen production, which often results in high CO₂ emissions. It is possible to capture and store the CO₂ emissions using carbon capture and storage (CCS) to produce low-emission blue hydrogen. However, the best method to attain a sustainable future is to produce green hydrogen using electrolysis powered by renewable energy sources. (25)

6. Environmental and Economic Considerations

Carbon footprint analysis is a dedicated and detailed estimation of greenhouse gas (GHG) emissions considering all relevant emission sources. As the main reasons for renewable energy systems is to reduce CO₂ emissions and fossil fuel dependency, the greenhouse gas emissions is an important parameter. The GHG emissions for hydrogen systems are different from other energy systems, thus methods for comparing the different systems are also different. The relative impact of hydrogen energy systems is still a debating issue, but most agree it will only increase substantially if large-scale systems are implemented. The CH₂G project has focused on comparing carbon emissions to that of natural gas reformation where 1 kg of hydrogen is produced from 2.7 kg of natural gas. This process typically emits 9-12 kg of CO₂, which is mostly vented to the atmosphere. In comparison, the steam reformation results equate to 3.6-4.6 kg of CO₂ for 1 kg of hydrogen, where 2-3 kg of the CO₂ result is stored and then released into the atmosphere. The partial oxidation and gasification methods emit around 3.3-4.5 kg of CO₂ per 1 kg of hydrogen. This carbon analysis has attempted to compare hydrogen production sources to that of the gas being reformed. An analysis comparing emissions from all hydrogen sources to all natural gas

sources was also conducted. This resulted in a wide range of data, so a key outcome was the creation of a model which could predict emissions to a high degree of accuracy, taking into account any changes in hydrogen production methods and conditions. This model is based on well-established thermodynamics principles and also the approximate algorithms which are used to simulate the hydrogen production processes. (26)

6.1. Carbon Footprint Analysis

Carbon footprint analysis of a large-scale H₂ energy storage and transportation system is carried out to evaluate its environmental performance compared to the natural gas and gasoline options. The analysis includes consideration of CO₂ emissions due to energy use, fugitive CH₄ emissions, and CO₂ emissions due to H₂ and O₂ leakage from the storage containment. Emissions from the H₂ system are compared to the relevant emissions from the incumbent fossil fuel system that it intends to displace (or in the case of OCGT backup, emissions displaced from a renewable electricity system). Although the carbon intensity of H₂ from renewable resources is zero, a non-negligible carbon footprint is associated with H₂ derived from fossil fuels via the catalytic SNG process. This is due to the carbonaceous energy source, where for a natural gas feedstock the overall process emissions are 22.4 kgCO₂ per GJH₂ and for coal 48.3 kgCO₂ per GJ H₂ (17). Considering an electrolysis efficiency of 68%, the storage and transmission system described in Section 5 and compression to 70 MPa, the specific energy use is 54.2 kWh kg⁽⁻¹⁾ H₂. Sparing detailed explanation the analysis results in total CO₂ emissions of 29.7 and 64.2 Mt CO₂ yr⁽⁻¹⁾ for natural gas and coal derived H₂. This should be contrasted with the global warming potential of both directly burned CH₄ and OCGT stack-emitted CO₂ at the rate of 221 kgCO₂ per GJ, or 76.9 Mt CO₂ yr⁽⁻¹⁾ with a comparable annual natural gas H₂ energy throughput, giving a significant net decrease in emissions with a switch to H₂. For renewable H₂ or H₂ from carbon capture, a realization of this storage and transmission technology would lead to a substantial decrease in emissions from the present day due to still H₂ energy. Leaked H₂ and O₂ are not greenhouse active and represent only a loss of energy storage; the leaks result in an effectively negative greenhouse gas emissions. An H₂ system provides a practical means of extra renewable electricity storage for intermittent renewables and would result in mitigation of curtailed renewable energy, the value of this in terms of reduced emissions will depend on the extent of renewables curtailment and is difficult to quantify. (27)(12)

6.2. Cost Analysis

One of the primary concerns of hydrogen fuel is the cost. It was discussed in Section 5.3 that the renewable energy input required to produce hydrogen is large. Also, in that section, a plant producing 160,000 tons of hydrogen a year was estimated to have a cost of sixty cents per kg. In this report, the production of green hydrogen was estimated to range from \$1.53 to \$2.57 in 2002, with an average of \$1.97. The primary cost of producing hydrogen is the price of electricity, so it is feasible that the cost could become competitive with fossil

fuel-derived hydrogen if the cost of renewable energy continues to decrease in the future. A recent study for the US Department of Energy showed that hydrogen from wind power can be produced at a cost of \$1.25/kg within the next 10 years. In 2006, the cost of hydrogen from natural gas was reported to be \$1.39/gal (which translates to \$1.86/kg). Considering the volatile cost of natural gas and the likelihood that a carbon tax will be imposed in the future, it seems that the cost of green hydrogen has a high potential to become competitive with natural gas-derived hydrogen. The transportation of hydrogen adds to the cost. For short distances, pipelines are the cheapest means of transport. The cost of hydrogen pipeline transport is related to the distance of transport, with typical cost ranging from \$0.02 to \$0.05 per mile per kg hydrogen. This is equivalent to a cost of \$0.3 to \$0.8 per 100 miles per kg hydrogen. At these rates, pipeline transport would add less than \$2 to the cost of hydrogen for a short haul of 400 miles. However, the construction of pipelines specifically for hydrogen has not been common in the past due to the small quantity of hydrogen production and low demand. This means that hydrogen pipeline infrastructure for large-scale transport currently is lacking, and as discussed in Section 4, using existing natural gas pipelines is not feasible due to hydrogen embrittlement of the metal pipeline materials. This would require new pipeline construction for large-scale green hydrogen movement. (28)

6.3. Policy and Regulation

Policy and regulation have the potential to drastically affect the prospects of green hydrogen energy in the near future, and of course its destiny longer term. A policymaker's decision to promote or discourage hydrogen power, or to support "traditional" or green forms of hydrogen, will clearly have an impact on the growth of green hydrogen technology. In the short term, green H₂ has a tough battle with grey H₂ in terms of production costs. Currently, there are no production subsidies for green hydrogen and it cannot compete with grey H₂. If a nation allocates funds to subsidize production of low-cost green hydrogen, it could accelerate the competitiveness of green hydrogen, which can be translated to global markets. This financial support is a double-edged sword; while it may nurture the growth of green hydrogen technology to the point where it becomes commercially viable, there is a risk it may create a reliance on government support and not allow the industry to stand on its own feet. Legislation regarding emissions and the implementation of carbon caps play a crucial role in determining the future of hydrogen energy. The Kyoto Protocol has been a major enabler for green energy technologies. Being a signatory to the Kyoto agreement commits a nation to a reduction in greenhouse gases and creates a market for low-emissions technology. With the implementation of an emissions trading scheme or a carbon tax, the costs of traditional energy will increase relative to low-emissions energy technologies. This provides an indirect opportunity for green hydrogen energy to be cost-competitive with traditional hydrogen and possibly more. (29)(30)

7. Advancements in Green Hydrogen Technologies

The search and manufacture of hydrogen using electricity rather than natural gas permits substantial flexibility in the selection of resources and technique. Electricity may be produced from renewable, nuclear, or fossil resources, and a term of the trade exists by choosing the foremost productive manner. Power and high-grade warmth can also be from solar thermal or fossil resources with CCS. For instance, nuclear or wind electricity can be utilized to manufacture hydrogen where the purpose is load-following electricity systems. Load-following power is well accommodated with nuclear power plants where their output is steady over daily periods, and altering the energy delivered to the system is more practical than selling power from an inflexible source like a wind farm. Although wind power that may well be curtailed can be utilized, and solar energy with surplus power periods may well be applied from when storage is predicted to be most beneficial. The proven fact that hydrogen is an energy carrier and not an energy source suggests that its production will be linked to the value of electricity, and when there's an abundance of low-value electricity, the mobile could stock energy for later use. Solid oxide electrolysis cells (SOEC) are an interesting option to low-temperature electrolysis and will yield hydrogen and syngas with a general thermal efficiency of 70-85%. This is much higher than today's hydrogen production from natural gas, often about 60%. SOEC is paired with solid oxide fuel cells to allow symbiotic hydrogen and electricity production for load-following energy systems. Otherwise, direct thermal hydrogen production from dissociating water or steam with a thermochemical copper-chlorine cycle exhibits very high efficiencies and can be paired with nuclear heat at very high temperature. (31)

7.1. Research and Development

To overcome initial barriers and to push the status of hydrogen technologies further, significant investment into research and development is necessary. Publications on hydrogen have seen a tremendous increase in recent years, providing evidence for the trend towards a "hydrogen economy". In the 1970s there were only a few publications per year, but in 2000 this had increased to around 50 and now it is close to and sometimes over 100 publications per year. Similarly, the amount of hydrogen-specific research and development projects has increased a large amount over the years with several national projects running and collaborations between various different nations (10). Most notable in recent years has been the announcement at the European Commission to increase funding for hydrogen and fuel cell technologies from approximately €700 million in the last 6 years to €1 billion over the next 2 years. Steadily increasing oil prices have also raised the stakes for hydrogen research, making alternative technologies such as fuel cells more attractive to industry and consumers. An overarching aim of these research efforts is to reduce the cost of hydrogen and fuel cells such that they are competitive with traditional technologies. Although this is a substantial endeavor, it is widely believed to be an attainable one. For instance, it is predicted that with

technical innovations and large-scale production, fuel cells can eventually be produced for a cost of \$30 per kilowatt, making them comparable with internal combustion engines (11). In order to achieve this level of cost reduction, many suggest that a transition through to hydrogen as an energy carrier is required, with the first step being a shift from hydrocarbons to hydrogen as a feedstock. This will allow for the development of infrastructure and technology for hydrogen energy systems, with the experience and expertise gained in this transitional period being crucial to the ultimate success of hydrogen as an energy carrier. (32)(33)

7.2. Technological Innovations

More radical but commercially unproven techniques for hydrogen production include the use of high temperature gas-cooled nuclear reactors and the use of solar furnaces to split water with the aid of heliostats and advanced solar thermal processes.

In addition to increasing the efficiency and reducing the cost of currently available methods for producing hydrogen, there are a number of more speculative methods with the potential to revolutionize hydrogen production. These include the development of artificial photosynthesis and genetically modified photosynthetic algae. If these techniques can be mastered, it may be possible to mass-produce biohydrogen at a cost similar to that of hydrogen produced from fossil fuels. Biohydrogen has the potential to be a negative emissions fuel as the carbon dioxide produced from combustion could be offset by the carbon dioxide captured during biomass growth.

Green hydrogen can be produced via many different techniques, and the efficiencies of these methods can be expected to increase in the future. This could result in a rapid increase in the rate of hydrogen production from renewables in the medium to long term. However, in the short term, the production of hydrogen from renewable energy is likely to increase at a slower pace. This is due to competition with cheap natural gas and the decommissioning of existing high-carbon hydrogen production plants. (34)(35)

7.3. Pilot Projects and Demonstrations

An important aspect, and currently the "hottest" area in hydrogen developments are the numerous pilot plants, studies and now a growing number of demonstration projects which are being undertaken across the globe. These represent the step between theory and full-scale commercialisation, and it is via these projects that the industry can test and validate different methods and technologies in a "real-world" setting. In the USA, one of the most publicised projects to date is the construction of a hydrogen powered internal combustion fuel cell bus (developed by Ford) and a fuelling station with provision for an electrolyser to generate the hydrogen, in the city of Las Vegas. This project has been funded by the Federal Transit Administration's National Fuel Cell Bus Program, and it is hoped that it will provide useful data and "lessons-learned" for a pathway to future hydrogen buses and stations. It will also provide information on the cost of hydrogen production using grid

electricity and PEM electrolyzers, and the reliability and maintenance overheads of such a system. This is just one example of a growing number of USA-based projects spanning a variety of different technologies and end-uses. The ECTOS project in Norway is working towards the establishment of cost-competitive hydrogen energy systems based on renewable energy. A key goal is to develop and demonstrate an efficient and reliable electrolyzer, which can be integrated into intermittent renewable electricity sources at a competitive cost. This could prove to be an important step in providing a method for storing surplus wind power. The hydrogen produced will be utilized in a number of different applications – as feedstock for ammonia production, a fuel for transportation, and for peak-shaving energy production. This project spans a number of years and has various phases, with the later stages involving a mini-grid energy system. This is just one of many interesting projects underway in Europe. Other regions in the world also have various pilot and demonstration projects, although it is beyond the scope of this article to cover them all. (36)(37)(38)

8. Challenges and Limitations

Looking at economic feasibility, Sanchez et al. explains that hydrogen has a high chance of becoming an economic energy carrier if aggressive research and development leads to a reduction in cost for the consumer. It is stated that the generic consumer is not willing to pay extra for a cleaner energy carrier. However, if the cost of hydrogen was comparable to other energy sources, there would be increased consumer acceptance and a greater chance of adoption of hydrogen energy systems. To bring the cost of hydrogen down to a level where the consumer will accept it, a price on carbon emissions in the form of a tax or cap and trade system would be necessary, providing an advantage for clean energy sources as opposed to fossil fuels, which release greenhouse gases but do not currently pay a cost for the environmental damage they cause. This speculative scenario advocates a carbon tax in which the revenue generated from it is put into research and development of clean energy sources, with the end result being lower costs for clean energy and a higher cost for fossil fuels.

As explained thoroughly throughout this review, numerous factors augment the potential of hydrogen once it reaches a state of economic feasibility. However, currently, several factors are limiting hydrogen from becoming a significant energy carrier. These factors vary from the question of economic feasibility itself to the infrastructure that must be implemented to allow hydrogen to be a true competitor in the energy marketplace. (6)

8.1. Scalability and Infrastructure

Widespread use of hydrogen in utilization technologies will require a large-scale hydrogen infrastructure. Projections on the demand for hydrogen and the form in which it will be used are speculative at best; however, the storage and transportation of hydrogen will be a necessary step in reaching a future hydrogen energy system. A preliminary estimate of future hydrogen demand suggests an eventual need to transport and store 35% of the total

primary energy used in the forms of oil, coal, and gas today. This is, in fact, a conservative estimate as it ignores the potential of hydrogen in distributed energy resources. High volumes and long distances of transportation will favor the centralized production of hydrogen, but the global nature of hydrogen in a future energy system suggests that hydrogen will be produced and stored in many different locales. Thus, it can be postulated that there will be various sizes and types of hydrogen storage facilities, ranging from large storage caverns to small storage tanks. The ability to match supply and demand and the economic feasibility of hydrogen storage and transportation will ultimately determine the true size and scope of a future hydrogen infrastructure.

Some general guidelines, which would allow for technically easier and cost-effective means of storage and transportation of hydrogen, require production of hydrogen at a price and scale competitive to the technology it is intended to replace. The end use of hydrogen will determine the scale and form of storage and transportation. Thus, the future needs and infrastructure requirements for hydrogen must be measured and quantified. A move to a hydrogen energy system will almost certainly be gradual, as both the supply infrastructure and the demand will develop over time. Thus, a move to hydrogen energy will take place in a series of steps, with the initial steps requiring smaller amounts of hydrogen and the quantities increasing until the final stage is reached. This gradual increase in hydrogen demand provides a timing mechanism, which will allow for matching supply and demand and a smooth transition from the present energy system to a future hydrogen energy system. (39)(40)(41)

8.2. Safety Concerns

Events of deflagration and detonation can cause significant damage if a hydrogen/air mixture is confined or released within a building or structure. Measures to prevent formation of explosive mixtures and to prevent leaks of hydrogen escaping into confined spaces are of critical importance in safety of hydrogen use, in particular with indoor or basement hydrogen energy systems if leaks can occur from other energy systems or if hydrogen is being used as a buoyant alternative to natural gas for heating and cooking. Regulations and codes have been developed for safe use of hydrogen and for promotion of safe design and installation practices for hydrogen systems, aimed at avoidance of past incidents and to prevent future safety issues with hydrogen as a new and alternative energy. Full manning and full implementation of these regulations and safety codes will be essential to manage the safety of a future hydrogen economy.

The potential of hydrogen to cause a detonation has been well understood for many years and is characterized by the detonation overpressure which can cause rapid pressure rise and significant damage from a high-pressure shock wave. Understanding of detonation events has allowed development of proven safety protection methods and has also led to release and detonation experiments to determine safe levels of hydrogen storage and to assess potential off-site impact of accidental releases of hydrogen. High-pressure hydrogen

storage systems which rely on a pressure relief device have stringent testing requirements to demonstrate safe release of stored hydrogen and to maximize the energy and mass of hydrogen which can be released before a detonation occurs, to ensure maximum safety in the event of accidental storage system fire exposure. These tests have helped to quantify safe levels of hydrogen containment and to develop safer pressure relief devices and hydrogen storage vessels. The potential fast energy release and flame damage from a hydrogen release presents a major concern for safety of intended use of hydrogen energy, which can be overcome by development of safe containment and utilization methods and provision of fail-safe devices to prevent hydrogen release during operation of hydrogen energy systems.

The lower explosive limit (LEL) for hydrogen gas in air is low (4%) and leaks of hydrogen can form explosive mixtures. Above the LEL, almost any mixture of hydrogen/air can ignite. Extensive research has been taken place to determine ignitability of hydrogen releases and subsequent flame and explosion hazards, to develop measures to prevent accidental hydrogen releases from leading to safety problems, to provide effective ventilation and confinement strategies when hydrogen is released and to provide safe detection and mitigation of leaks of hydrogen. (42)(4)(6)(7)(43)(44)

8.3. Energy Efficiency

The final challenge facing the hydrogen economy is that of ensuring the most efficient use of primary energy in producing, storing, transporting, and converting hydrogen into useful energy. There are three different but connected issues in considering the energy efficiency of hydrogen energy systems. First, it is an issue of the competing cost of using primary energy in the hydrogen energy chain compared to more conventional energy systems. For instance, using hydrogen fuel cells as opposed to more efficient hybrid electric vehicles powered by batteries and an internal combustion engine running on gasoline. In order for renewable hydrogen to compete with conventional energy sources, the renewable energy used to produce the hydrogen must already compete economically with fossil energy sources. Though hydrogen production is considered by many as quite inefficient, it is still possible for hydrogen to compete cost-effectively with other products of renewable energy in situations where energy from a variable renewable resource is produced in excess and would be. Second is the efficiency of the different stages in the hydrogen energy chain, including hydrogen production, storage, and end use. High efficiency can be said to be greater than 43% and is a reasonable target for the development of hydrogen production and storage technologies. High-temperature steam electrolysis is proposed to be an efficient method of hydrogen production with heat-integrated nuclear or solar processes. High-temperature electrolysis, as an overall efficiency approaching 50% if process heat is around 35% efficient at a temperature of 700°C, can be achieved. Underground hydrogen storage, presumably in salt caverns. (45)(46)(5)

9. Case Studies

Of the varied strategies mentioned, underground storage is considered to be the most promising, given that it has been finished in big scale for the storage of natural fuel. It's also the most promising for the garage of huge volumes of hydrogen for periods of weeks to months. The technology for storing hydrogen as a hydride or in chemical form is still in developmental tiers, and is most effective taken into consideration to be feasible in situations where the alternative is not viable. Underground storage is an answer to each these methods. The studies which has been carried out on hydrogen permeation and embrittlement will virtually be critical to the continuing development of this storage method, as pipeline infrastructure is already a attempted and tested method of transporting gases worldwide.

The research undertaken in this essay is designed to provide an exhaustive review of the advancements in large-scale hydrogen storage and transportation. Given the infancy of the industry, the preferred cause of budding hobby in hydrogen should be supported via authorities policy and delicate regulation. It's also apparent that given the scope of the various suggestions outlined for storing hydrogen, tailored answers—each technically and economically—to the storage of precise forms of hydrogen are required.

9.1. Large Scale Green Hydrogen Projects

An advanced adiabatic compressed air energy storage and hydrogen power generation project known as HELMETH (highly efficient power generation with a mixture of thermal and electrical power) has also been conducted in Germany but was also terminated after successful testing of the prototype due to funding issues. Storage and power projects are valuable demonstrations for utilizing surplus renewable energy and still hold potential for development with the progression of energy systems towards sustainability.

Storage of hydrogen for energy shifting and peaking power is another feasible application that has been demonstrated by projects in Germany and the United States. California was planning to use electricity from wind power to perform electrolysis and generate hydrogen to be stored at PG&E's depleted underground natural gas reservoirs. Unfortunately, this project was terminated in 2013 after 7 years of planning due to concerns on high costs and long term commercial viability.

The endeavor in Germany is similar, aiming to establish a sustainable energy system for transportation using renewable energy, especially wind power. Hydrogen refueling stations are being built at existing conventional station sites and also integrated with solar powered stations as a means to demonstrate the viability of H₂ from renewable energy. The overall success of these projects can significantly reduce vehicle emissions and increase the demand for green hydrogen.

California has been recognized as a leading state in promoting sustainable energy, and its recent commitment to fuel cell vehicles has established an opportunity for transitioning transport away from internal combustion engines. The construction of hydrogen refueling stations has been undertaken by various automotive and energy companies, and the state plans to have 100 operating stations to coincide with the release of Toyota's fuel cell sedan in 2015.

Through importing natural gas for hydrogen production, Norway has been able to divert from using a domestic energy source: hydropower. Australia also intends to use natural gas steam reforming for the production of hydrogen via creating ammonia. However, to neutralize the emissions of these projects, both countries seek to implement carbon capture and storage of the CO₂ and are candidates for significant funding.

Large scale green hydrogen projects focus on analyzing the status and characteristics of several large scale hydrogen projects that have used or intend to use green hydrogen. The projects are assessed on their ability to internalize external costs for the environment and the project's effect on developing sustainable energy systems. The selection consists of ammonia production in Norway and Australia, fuel cell vehicle transportation in California and Germany, and hydrogen energy storage in Germany and the United States. The ability for these projects to internalize external costs is a key factor in their success in aiding sustainable energy development. (47)(48)(42)(49)(50)

9.2. Successful Integration Examples

The produced hydrogen would be used in the transport sector, replacing diesel with fuel cells, and the CHP production of electricity and heat. This can be seen as a smart response to the problem of intermittent energy sources and an effective way of storing wind energy at a time when Europe has pledged to increase renewable energy to 22% by 2020, with 12% of that being wind power.

The case of wind power and hydrogen in Schleswig Holstein, Germany is an interesting example of rationalizing energy consumption and production when wind power was found to be occasionally being sold for a negative price. The excess wind power being produced at these times presented an economic and environmental opportunity for the region, but some wind farms were forced to shut down to prevent grid destabilization, resulting in loss of potential revenue. It was decided that the best option was to install electrolyzers and utilize the excess wind power to produce hydrogen to be stored and used as an energy carrier with the added benefit of being able to utilize the hydrogen as a means of energy storage and transport.

The successful integration of hydrogen can be seen in a range of applications. Case studies are given that show the deployment of hydrogen in a number of different energy systems. These include the use of wind power and hydrogen in Schleswig Holstein, Denmark and

the Canary Islands, the utilization of hydro power and electrolyzers in British Columbia, and the recent hydrogen fuel cell installations in North America. These cases give a broad overview of the potential for hydrogen to be integrated into various renewable energy systems. (51)(52)(53)(54)(55)

9.3. Lessons Learned

With an immature technology state and high uncertainty in future energy markets, it is critical that governments provide long-term direction and supporting policy frameworks for renewable hydrogen projects. It is concluded that the supportive renewable energy policy was a key driver of the increase in renewable energy investment in Australia and the development of renewable hydrogen projects. A supportive policy framework can give assurance to private sector investors in both short and long-term financial market conditions, it can reduce uncertainty in future energy market developments and assist coordination of renewable hydrogen projects with developments in renewable energy generation. A stable renewable energy target can align the renewable hydrogen sector with the renewable energy sector, reducing conflict with fossil-based energy production and hydrogen technologies. It should be noted that Korea's green growth policy (2008-13) aspired to become a lead market for green industry, increase employment, and build a low carbon high growth economy; in this context, it is hoped that there will be supportive policy frameworks for KIER's hydrogen projects.

Apart from specific project details, several key features are noted as being important for future projects: project implementation should use and add to existing industrial infrastructure where possible (DAIS, KIER project), in this way local development projects can enhance existing trading patterns within the community. The mode of renewable electricity procurement is key; long-term purchasing agreements can underpin the financial security of hydrogen projects, but without government support or a steadily rising electricity market price, it could detract from the renewable electricity generation sector. Partnership with a technology provider can be beneficial to share technology development risk and access technology at reduced rates, sharing facilities (such as the ECN Windmolens op Zee project in the Netherlands) can also lead to cost reductions and consolidation in the technology development phase. (56)(57)(58)(59)

10. Future Outlook

The concept of hydrogen storage has been around for a considerable period of time. While there have been negligible strides in the way of hydrogen storage for the support of renewable energy, recent advancements have propelled hydrogen as a viable storage solution. In particular, renewable production of hydrogen is a major step towards sustainable energy storage. Renewable hydrogen can be produced in a number of ways, and potentially stored for extended periods of time. With the ability to produce hydrogen from renewable sources such as biomass or electrolysis of water, this allows for the possible dissociation of being able to store renewable energy in a non-renewable form of

energy. This creates a reliable backup storage of energy that can be converted back into electricity using a fuel cell, and the only byproduct would be water. This could effectively bring an end to the intermittent energy that comes with the supply of solar and wind-powered systems. While hydrogen can be utilized as a storage medium for renewable energy, it also has the potential to be an energy carrier for renewable energy. This is particularly relevant to large-scale utilization of solar and wind power which may be deployed in remote areas far from major load centers. By converting and storing energy from renewable sources into hydrogen, it can easily be transported via trucks or pipelines to areas where electricity generation is not feasible. Once it reaches its destination, it can be converted back into electricity using combined cycle generation or fuel cells. The utilization of renewable hydrogen as an energy carrier can effectively connect remote energy resources to the electricity grid. Large-scale production of hydrogen will lead to a significant reduction in the cost of hydrogen fuel cells, which can be used for a myriad of applications. This includes vehicles, portable electronics, and residential power generation. While the cost of fuel cells has been steadily decreasing, the cost of hydrogen from renewable resources is still quite high compared to hydrogen from natural gas. This is due to the fact that renewable energy is inherently intermittent, and an electrolyzer must be able to produce hydrogen on a 24/7 basis. Storage of renewable hydrogen is still relatively expensive due to the fact that current storage methods such as underground caverns or salt domes are tailored towards storage of natural gas, and storage of hydrogen has different requirements. By increasing the demand for hydrogen as a storage medium and an energy carrier, it can be expected that more hydrogen storage projects will be deployed, and further research will be done on the optimization of hydrogen storage, leading to a reduction in the cost of hydrogen storage. In the long run, this transformation into a renewable hydrogen economy could create a sustainable energy ecosystem and reduce the reliance on fossil fuels. This could be the beginning of a massive overhaul of energy infrastructure, similar to the construction of the large-scale natural gas infrastructure in the 20th century. The end result would be a vastly different energy industry and a cleaner environment due to a reduction in emissions.

(60)(61)(62)(10)(1)(63)(10)

10.1. Potential for Growth

Although the forecasts for hydrogen use are quite optimistic, many of these scenarios have not been realized. Presently, the majority of hydrogen is still produced from fossil fuels and used for various industrial applications. The transition to a sustainable hydrogen energy economy will require a concerted effort on a number of fronts.

As discussed earlier, the production of hydrogen can serve as an energy carrier. The production of hydrogen can be integrated with renewable energy sources such as wind, biomass, or nuclear energy to provide an environmentally cleaner source of energy. Studies have shown that the use of renewable electricity to produce hydrogen for use in fuel cells

results in a significant reduction of greenhouse gas emissions compared with the direct use of renewable electricity in batteries or with renewable or conventional energy sources in internal combustion engines.

The rising global demand for energy, coupled with environmental consciousness, is driving research and innovation in the field of sustainable energy. Hydrogen is considered to be the most fuel to meet this demand, as it is a versatile and clean-burning fuel that can be used for a variety of end-use applications, including chemical and refining industries, metals processing, transportation, power production, and residential fuel. Hydrogen fuel cells can be used to power emission-free electric motors, and hydrogen may be burned in internal combustion engines with emissions largely limited to nitrogen oxides. In recent years, the focus of hydrogen energy research has shifted from end-use technologies to a greater emphasis on the use of hydrogen in the context of a more sustainable energy system. (64)(16)(65)(5)(63)

10.2. Emerging Trends

The main target of hydrogen technology will be implemented in the transportation sector since it is decreed that the usage of hydrogen is more beneficial compared to other energy carriers. Currently, the most commonly implemented hydrogen technology in the transportation sector is the utilization of fuel cells. The result of the fuel cell reaction, which is electricity, can be used to move the motor vehicle, and the only byproduct is water, so it does not contribute to air pollution. In the beginning, Europe was developing fuel cell technology through a collaboration between the private sector and government, through a research consortium called the Joint Undertaking for Fuel Cell and Hydrogen Technology (JTI FCH). One success from this research is the implementation of fuel cell technology in public transportation. An example is the development of fuel cell-based buses, which have been used in some European cities such as Amsterdam, Barcelona, Hamburg, and more. After that, the development of fuel cell technology moves to the next phase, which is implementation in individual transportation. This phase is still ongoing, as seen from some car manufacturers offering fuel cell-based cars for consumers.

Introduction of real finally, hydrogen has been recognized as a potentially sustainable energy carrier that can be helpful in satisfying the continuously increasing worldwide energy demand and limiting the environmental destruction caused by releasing greenhouse gases. The major advantage of hydrogen is that it is sufficiently abundant. It is estimated that 75% of the known universe is composed of hydrogen. In addition, hydrogen is an energy carrier that can be produced locally and reduce the energy loss incurred during the transport process. In the long term, hydrogen has the potential to make a transition for the world energy system from fossil-based to the sustainable one, which is renewable energy-based. All these benefits of hydrogen have also been realized by the European Union. In the Power of Vision, the President of the European Commission announced that hydrogen can contribute to enhancing energy security and competitiveness in the European Union

while also reducing the effects of greenhouse gases. To support this vision, the European Union has committed to increasing the use of renewable energy sources, including the use of hydrogen as an energy carrier, by announcing the Renewable Directive policy to reach a 20% target of energy derived from renewable energy sources by 2020. (66)(67)(68)(5)

10.3. Policy Recommendations

Governments should formulate clear guidelines to regulate investment in hydrogen energy and ensure it will be used in environmentally friendly and sustainable systems to achieve climate change and energy security goals. Early policy intervention is necessary to develop CO₂ capture and storage and renewable energy sources because hydrogen production systems are capital intensive and long lived. Given the right signals, hydrogen could form the link between increasing renewable energy and sustainable transport, thus helping to reduce the impact of very large renewable energy sources on the existing electricity infrastructure. This could be achieved by mandating a certain percentage of new electricity capacity comes from renewable sources and further legislation to promote use of renewable energy in hydrogen production. This could involve tax breaks or subsidies for green hydrogen producers using renewable energy sources. International collaboration is vital in stimulating hydrogen energy technology and cost reduction through shared expertise, pooled funding and shared research programmes. It also has implications for trade in energy resources and the environmental industry as exporting hydrogen and fuel cells can provide a means to increasing GDP for countries rich in renewable energy resources. This is particularly relevant for Europe where Japan, having no domestic energy resources, has earmarked Australia as a partner to supply hydrogen produced from brown coal and natural gas with carbon capture and storage. Lastly, public awareness and acceptance of hydrogen energy is essential and this can be achieved by government showcasing procurement in the public sector as was the case with fuel cell electric vehicles in California. (69)(17)

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