Hydrogen production, storage, and transportation and grid line support application

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Abstract. The clean energy demand worldwide has increased significantly with the increase in population. One of the most potential candidates to fulfill the energy requirements is renewable resources, and the most environmentally friendly fuel is hydrogen. This study concentrates on hydrogen technology and introduces its production, storage, transportation, and gridline support application. Results show that methane steam reforming and electrolysis of water are common hydrogen production methods. The electrolysis of water technique can be close to renewable energy source because of device simplicity. In addition, produced hydrogen gases or liquid are stored in natural sites such as salt caverns or vessels made of metals, polymers, and composites. The composite hydrogen vessel benefits from light weight and high-pressure limit for movable storage such as transportation, while the low-cost metal container fits the purpose of stationary storage. The fuel cell can power electric motors for busses and cars without a carbon footprint by burning hydrogen gases. Finally, the physical storage of hydrogen gases or liquid can have high scalability to store seasonal fluctuation of renewable energy to gridline.

1. Introduction
In 2020, petroleum energy was about 35% of the US energy consumption, and a major amount of petroleum energy is used in the transportation sector [1]. The internal combustion engine has particulate emissions, including sulfates and soot, air pollutants [2, 3]. Scientists and businesses are devoting more resources to renewable energy and clean transportation tools with the increasing concern over global warming due to carbon emissions. The Paris Agreement, adopted by 196 countries and regions, has set a goal to achieve only 2 degrees Celsius of increase than the preindustrial levels [4]. Without any carbon neutralization technology, the binding members of the Paris Agreement focus on reducing greenhouse gas emissions to stabilize the amount of carbon dioxides in the atmosphere [4]. The immediate effort of greenhouse gas emission control is valuable to reach the peak of greenhouse gas emission and finalize the global temperature increase from the pre-industrial era.

With the air pollution and carbon emission, petroleum is not ideal energy. Moreover, it is also not eternal since the projection of oil reserves can only last 40-50 years. Therefore, scientists are innovative about renewable energy sources, from dams' hydropower to photovoltaic cells' solar energy. For example, solar cells and wind turbines increase renewable energy source capacity by 50% from 2019 to 2024 [5]. Even though renewable energy is environmentally friendly, the produced energy might not be universal. Taking wind turbines as an example, they are located from remote meadows to offshore sites. The transportation of generated power will cost users for every mile traveled on the grid line due to the voltage drop after electricity conducts in a wire. To deal with asynchronous energy consumption and upsurging of storage demands, hydrogen technology could be a clean way to bridge the renewable energy to clean transportation due to the localized production with electrolyzers.
The hydrogen gas has a higher specific heat per mass than other fuels, which gives the high density of energy storage in a unit mass. It’s more effective to carry huge amounts of energy from hydrogen than the same load of petroleum. Also, the hydrogen reservoir is easily scalable by using a larger container made from composite materials. The container has a simpler structure and is cheaper than the battery units. More importantly, the only emission of a hydrogen fuel cell is water which leaves no harm to the environment, and automobile manufacturers such as Toyota have proven the feasibility of hydrogen fuel cell cars [6]. Overall, hydrogen's physical and chemical properties give fundamentals for the wide adoption of hydrogen technology in the future. With increasing renewable energy for electricity supply, a transportation system by recycling water applied in hydrogen production can dramatically decrease the carbon footprint from petroleum engines.

The previous research about hydrogen techniques only focused on separate parts of the whole picture of the hydrogen economy. Elberry Et al. and Andersson Et al. thoroughly discussed stationary hydrogen storage using hydrogen vessels and geological storage [5, 7]. Squadrito Et al. presented the merits and the limitations of hydrogen fuel cells [8]. In addition, government agencies such as the Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) have reported buses with hydrogen fuel cells and possible hydrogen storage design use wind turbine towers. Based on the detailed interpretation of major scientific terms and concepts, this study introduces the intact process of the big name and hydrogen economy from the production, storage to the final application, which can be a starting point for a more detailed illustration of the hydrogen economy from industry to daily life.

2. Hydrogen production process and principle

The electrolysis of water produces hydrogen with the supply of electricity which renewable energy sources could harvest. Currently, the most common hydrogen production method is Methane Steam Reforming (MSR) due to the higher cost of hydrogen electrolyzer [9].

2.1 Electrolysis of water

In general, renewable sources drive electron movement by electrical potential or mechanical work from turbines to generate electrical energy. The electrolysis of water can produce hydrogen and oxygen from water with the electricity supply shown in Fig. 1.
The device is composed of a cathode, an anode, and polymer electrolyte membrane (PEM). PEM conducts excessive hydrogen ions or protons from the anode side to the cathode side, balancing the charge in the reactant water. With the electricity supply, the cathode reaction produces hydrogen gases, and the anode reaction produces oxygen gases. The ratio of hydrogen and oxygen gases is two to one because of the composition of water molecules. The electrolyzer device has a simple setup and can be localized to renewable energy sources such as wind turbines and solar panels.

2.2 Methane Steam Reforming (MSR)

In industry, hydrogen gas is most commonly produced through methane steam reforming (MSR). The MSR contributes to 50% of global hydrogen production and 95% of the hydrogen consumption in the United States [11]. The MSR uses methane and water as reactants and produces hydrogen and carbon dioxide, shown by the equations below [11]:

\[ CH_4 + H_2O = CO + 3H_2 \quad \Delta H_{298K}^0 = 206 \frac{kJ}{mol} \quad (1) \]

\[ CH_4 + 2H_2O = CO_2 + 4H_2 \quad \Delta H_{298K}^0 = 165 \frac{kJ}{mol} \quad (2) \]

\[ CO + H_2O = CO_2 + H_2 \quad \Delta H_{298K}^0 = -41 \frac{kJ}{mol} \quad (3) \]

In figure 2, the methane and steam are supplied from the left side with air and fuel from the bottom of the reactor. The mixture of water gas will then go through a high temperature and low-temperature reactor before the product separates into different cylinders. Nickel metal contributes to 62% of the catalyst used in MSR reaction because the nickel-metal is cheap, and it has an acceptable coke formation resistance which promotes the catalyst lifetime.

Some researchers argue that hydrogen technology will not relieve global warming because the hydrogen production process emits carbon dioxide even though the only product of burning hydrogen is water. Hydrogen production indeed emits carbon dioxide. However, according to the Environmental Defense Fund (EDF), methane has 80 times more global warming effects than that of carbon dioxide when the methane is present in the atmosphere for the first 20 years [12]. In the short term, the conversion of methane to carbon dioxide in the hydrogen production process can dramatically relieve the global warming effects. The immediate process can help contribute to greenhouse gas emission to peak out and establish stabilization earlier.

3. Storage of hydrogen gas

Hydrogen is commonly stored in three categories: physical storage, adsorption, and chemical storage [7]. Hydrogen is conventionally stored by physical storage as compressed gas or liquid phases. The
physical storage methods are scalable, and an advanced material selection design can bring a wide range of storage pressure. It can be stored in special containers or underground.

3.1 Vessel storage

The construction of containers is not complex, and the choice of material selections should be satisfied with the various mechanical properties of hydrogen gases. Metal and composites are the two most common materials for the physical storage of hydrogen. Carbon steel and low alloy steel can withstand 500 bar maximum pressure hydrogen storage and ensure the system's safety and stability [5]. However, the weight of steel restrains mobility which leads to incentives of introducing nonmetal materials and adopting composite designs for reduced weight of containers. The typical composite design contains a metal liner wrapped by high-strength and high-stiffness fiber resin composites, which hold up the 450-bar maximum pressure and has only half of the weight of only-metal design [5]. More advanced vessel design further replaces the metal liners with composites or reduces the thickness of metal liners with high-strength metals that hold up to 1000 bars of compressed hydrogen gases [5]. Therefore, the introduction of composites increases the strength-to-weight ratio and the cost of construction at the same time.

However, the interaction between hydrogen gases and the materials can cause some issues, such as hydrogen embrittlement. It refers to the diffusion of small-size hydrogen particles into the solid solution of steel. Typically, the hydrogen can fit into the interstitial sites in the microstructure. The hydrogen atoms can increase the mobility of dislocations which propagates more plastic deformation with more slip planes. The effect of hydrogen embrittlement can lead to more cracks on the surface of metals. In general, hydrogen embrittlement can lead to catastrophic failure of high-strength metals due to their brittle nature. As a result, the hydrogen embrittlement imposed a dilemma on adapting high-strength metals for vessel design. Other polymer parts in the hydrogen system can lead to gas permeation, leaving room for hydrogen to diffuse out. Despite the fundamental physical and chemical change of the polymer properties are unknown, the gas permeation can change the pressure of the container, which can possibly cause deformation [5].

3.2 Storage at Renewable Source

The specified container for hydrogen gas storage can have trade-offs among physical properties and construction costs. Recently, many researchers started to consider possible hydrogen solutions from existing structures and suitable natural conditions. Wind turbine tower interior is one solution that connects hydrogen storage to renewable energy [the patent no. US 7471,010 B1] [13]. The hydrogen is designed to be stored at the lower part of the tower, and the equipment for wind turbine operation will be located outside of the tower, as shown by the orange region in Figure 3. With installing a hydrogen electrolyzer at the bottom, the electricity from the external power transmission cables (shown in red lines in Figure 3) can be converted into hydrogen gas for storage inside the tower. According to NREL, a container with 940-kilogram hydrogen will cost $83,000 to install on a wind turbine tower [13]. With the existing wind turbine tower structure, the cost of each kilogram of hydrogen is $88, which is only one-third of the cost of conventional pressure vessel storage methods [13]. In addition, the hydrogen embrittlement effect in the wind turbine tower can be negligible because the wind turbine towers are designed to hold the aerodynamic stresses from the wind [13]. Despite the lack of successful engineering and thorough investigation of the design parts, storing hydrogen gas in wind turbine towers is promising to localize the hydrogen storage and production for renewable energy.
3.3 Geological Storage

The geological storage commonly utilizes the extracted sites of natural gases and salt caverns. The cushion gas refers to the base gas that maintains the pressure of the system and the gas deliverability [5]. In contrast, the working gas refers to a gas that is constantly retrieved and refilled [5]. The operation starts with injecting gases into the depleted natural gas reservoir and seals the top cap with hydrogen-impermeable rocks [5]. The cost of the storage construction is as low as $1.23 per kilogram because of the existing equipment and construction from extracting sites [5]. Moreover, salt beds can also be used as hydrogen storage units by leaching the salts out, known as salt caverns. The salt cavern is one of the most promising hydrogen storage solutions that has been implemented in many countries, including the US, Britain, and Germany [5]. The salt caverns have a small depth which only requires a little cushion of gases. In addition, the salt in the salt cavern can prevent gas permeation which gives rise to a stable storage system. Considering the substances used to leach the salt, the construction cost could rise to $1.61 per kilogram of hydrogen stored [5].

4. Transportation and Grid applications

4.1 Hydrogen Transportation

The hydrogen fuel cells consume gaseous hydrogen to generate electricity which could be used for electric motors in transportation and grid support. The hydrogen fuel cells preserve the chemical reaction of the electrolysis of water so that the emission of consuming hydrogen fuels is zero. In figure 4, the hydrogen fuel and air enter from the left and right sides, respectively. The electrolyte, also known as the proton-exchange membrane (PEM), is only permeable to proton or hydrogen ions. The imbalance of positive charges establishes a potential difference or voltage, which promotes the movement of electrons through the external wire to generate current and electricity. Real devices of hydrogen fuel cells have a thin anode, PEM, and cathode, which can be stacked together to generate electrical powers at different levels.
Hydrogen fuel cell vehicles (HFVCs) are realities for both public and private transportation. In the US, 24 out of 26 fuel cell buses were active in service for demonstration purposes [15]. Specifically, AC Transmit is currently operating 12 of those in the San Francisco Bay area, CA, for demonstration purposes [15]. According to AC Transmit, each HFVC runs 250-300 miles when fully refueled and stores 50 kilograms of hydrogen gases at 5000 psi (around 350 bars) that are aligned with hydrogen tank type 3 by the DOE [16]. The vehicle performance fits into the requirement of a city bus transit, and many improvements are still possible given the model year of AC Transmit HFVCs is 2005. Public transportation has fixed routes and refueling schedules where the fuel storage can be centralized. However, the wide application of private automobiles requires hydrogen refueling stations (HRS) to a competitive number of locations as the petroleum stations for convenience.

4.2 Hydrogen Refueling Station (HRS)

The Hydrogen Refueling Station (HRS) is the most important infrastructure construction for the practically convenient operation of hydrogen vehicles. The National Fuel Cell Research Center (NFCRC) at the University of California, Irvine (UCI) launched the first HRS for the public in 2003 for pre-commercialization purposes, which support all the manufactures of fuel cell electric vehicles (FCEV) [17]. The first HRS only completed 76 successfully refueling until an upgrade on the system because of reliability issues of the system design [17]. By the end of 2020, 45 HRS are active in the retail sales in California, where the majority of the HRS in the U.S. is concentrated, and 16 additional HRS are planned to be constructed by the energy commission of the state of California [18]. The state-of-the-art HRS station design is the “Gen IV”, shown in Figure 5, which contains the compressor, high-pressure storage tubes, and condensers in a closed container with a removable tube trailer for hydrogen delivery [19]. The Gen IV HRS renders hydrogen fuel to light-duty passenger vehicles at 350 or 750 bar with a capacity of 180 kilograms of hydrogen per day [20].
The Gen IV HRS is evolutionary to the commercialization of hydrogen fuel because the yearly tons of hydrogen and yearly fills have dramatically increased after the transition from Gen III to Gen IV. During the 5 years of operation, the daily refilling increased to 300 kilograms with the highest of 397 kilograms, leading to pressure on the designed 180 kg capacity of each pump position [17].

Figure 5. The schematic of the Gen IV Hydrogen Refueling Station [19]

Figure 6. The statistic of the amount of hydrogen rendered and numbers of fills over years and generation III and IV Hydrogen refueling station [17]

Figure 7 shows the exemplary hydrogen storage tank to deliver hydrogen to the local HRS with several cylindrical tubes in a rectangular frame. The black lines and dots indicate the metal frames and the attaching points, respectively [21]. According to the manufacturer, the hydrogen vessel is all
composite designs that conform to the Type IV design mentioned in the hydrogen storage part [21]. The composites have the desired mechanical strength to hold the required pressure and light weight for better fuel efficiency during the delivery transportation. In addition, the all-composite design avoids the corrosion and fatigue issues in the Type I vessel [20]. The successful regional application proves the feasibility of HRS station construction. In the future, the hydrogen can be delivered similarly to the gasoline pipelines, which significantly reduces the price add-up from hydrogen production to individual users.

![Figure 7. the schematic of a hydrogen trailer designed by Hexagon Lincoln corporation [21]](image)

4.3 Gridline Power Balance

The renewable energy source is highly dependent on an external environment known as seasonal. For example, the sun illumination changes the incident light intensity and heating to different parts of the atmosphere to alter the wind pattern, which varies the energy harvested by solar cells and wind turbines. The variation of energy supplied by energy storage methods to avoid drastically increasing energy prices or negative prices. Even though the negative price can be beneficial to users as consuming electricity brings profits, the industry is worried about the possible ceasing of production of conventional power plants, which could lead to long-term grid instability [22]. The battery is one of the most common energy storage units in our daily life. The lithium-ion batteries support portable devices such as laptops and cellphones, and the lead-acid battery powers all the electronics in vehicles.

The consumer batteries are engineered to be light, small-size, and high power (quick discharge in a unit of time), as shown in Figure 8. However, the battery has limited capacity and poor scalability (small module size) for the grid support [23]. Moreover, the discharge of electricity, lifetime, and toxicity of battery design reduce the application of batteries as long-term storage units [23]. On the other hand, the hydrogen is easily scalable with a larger tank-size for sufficient energy storage capacity. The discharging rate of hours is reasonable to accommodate the variation in the grid with weather forecasts. Hydrogen storage has more financial drawbacks because of the cost of hydrogen production equipment, including electrolyzer than the most used mechanical storage such as pumped hydropower storage [24]. At the same time, hydrogen storage is environmentally friendly, and hydrogen production is close to renewable sources. With more research and development to further reduce the cost of hydrogen-related devices, hydrogen is one of the most viable storage candidates for the future clean energy economy.
Figure 8. the discharging rate of electrical, electrochemical, thermal, mechanical, and hydrogen-related energy storage from 1 kilowatt to 1 gigawatt [24]

5. Conclusion

The review demonstrated the methods of hydrogen production, storage, and real application on transportation and gridline support. The hydrogen is most commonly produced by Methane Steam Reforming (MSR) for industrial purposes. At the same time, the electrolysis of water is more suitable for pairing with renewable energy sources such as solar energy. The device for electrolysis of water benefits from the simple structure, but the cost of a proton-permeable membrane adds up to the overall cost of the system.

After the production of hydrogen, the hydrogen is stored in vessels or natural sites for energy consumers. The hydrogen vessel is classified into four categories (Type I, II, III, IV), containing mainly metal material to composite structure. The composite vessels provide high strength and low weight, which fits into the mobile storage of hydrogen gases or liquids such as delivery tanks or hydrogen vehicles. On the other hand, the mainly metallic vessel is relatively cheap to construct for large stationary storage, yet the solution to hydrogen embrittlement is still under research. The hydrogen storage might utilize geological sites such as salt caverns and abandoned nature gas extraction sites. Those geological sites have the suitable properties to store hydrogen gases, but the location of available sites limits the application. Lastly, scientists are actively searching for ways to store hydrogen close to renewable energy sources. The storage tank inside the wind turbine tower is one of the most promising solution in term of compatibility and cost effectiveness. The wind turbine tower has internally sufficient space for a hydrogen tank, and the constant aerodynamic stress under the normal wind turbine tower working condition proves the structural stability under the condition of turbine towers.

The hydrogen application is not far away from our daily life. With constant routes and hydrogen gas refueling, the hydrogen fuel cell buses provide green and affordable transportation to city residents. The wide commercialization of hydrogen fuel cell vehicles requires the same level of convenience to customers as that of internal combustion engines. For general use of hydrogen fuel cell vehicle, the
researchers and government had set clear standards and operation procedures for hydrogen refueling station (HRS). Because the unpredictable nature of renewable energy depends on seasons and weather, the hydrogen and fuel cells are applicable to balance the gridline when the energy production or consumption is excessive for the time scale of hours.

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