Feasibility Investigation of Several Hydrogen Generation & Storage Methods

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Abstract—Sustainable development has always been one of the main agendas of countries all over the world, where energy issue is always a significant part of sustainable development. Finding a clean and sustainable energy to replace highly polluting and nonrenewable energy (e.g., fossil fuel) is one of the main goals of sustainable development. As a clean, safe, efficient energy with a wide range of raw materials, hydrogen is one of the important topics in energy research. Based on the goal of sustainable development, this paper selects a part of hydrogen production, transportation and storage methods for analysis. According to qualitative and quantitative investigation, this paper illustrates the feasibility of large-scale application of these methods. In addition, this paper will also explore the future development prospects of these technologies. These results offer a guideline for further development and implementation of hydrogen energy.

1. INTRODUCTION

Economic development is always accompanied by environmental damage, and becomes more and more intense since industrialization. Various environmental problems have plagued human society for a long time. Contemporarily, sustainable development has become one of the main issues of the United Nations and major countries. It is necessary to pay attention to environmental protection while developing economy.

Energy issues are one of the important components of sustainable development. It is an important material for human survival and development. With the development of technology and the scientific innovation of energy utilization, human beings pay more and more attention to whether our energy is eco-friendly and traceable. Looking for new energy has become one of the urgent tasks at present. As a clean, safe, efficient energy with a wide range of raw materials, hydrogen is widely used in the industrial field. It is one of the main directions of new energy development. It is believed that hydrogen energy will become an important energy source in the future.

This paper introduces the sustainable development goal of this study from the perspectives of environment and economy. On this basis, the objects of this research are selected. In the hydrogen production method, water electrolysis is chosen as the main research object. As for hydrogen transportation methods, various methods are introduced in this paper. Hydrogen storage methods are divided into material-based storage and physical storage, where physical storage is to store hydrogen in various forms (solid, liquid and gas) while material-based storage is to adsorb hydrogen to storage materials through chemical reaction. In the physical storage methods, the liquid hydrogen storage is selected as the research object. Because there are too many kinds of storage materials in the material-based hydrogen storage method, it is difficult to identify their features in detail, i.e., material-based hydrogen storage method will not be discussed in this study. This study carries out a qualitative and quantitative investigation on these technologies and methods, expounds their advantages and
disadvantages, makes a feasibility study on them, as well as analyzes the current large-scale use feasibility and future development prospect of these technologies and methods.

2. SUSTAINABILITY GOALS

The sustainability goal of our study is divided into two aspects: environmental goal and economical goal, which is as follows:

- Environmental: Eliminating greenhouse gas emissions to the atmosphere towards a clean and green energy future for sustainable development.
- Economical: Investing in new energy technologies in order to make it become more affordable, accessible, and cost-effective for sustainable development.

In order to achieve the sustainability goal, it is necessary to investigate clean, safe, efficient and cheap energy. Hydrogen is divided into grey hydrogen, blue hydrogen and green hydrogen. Grey hydrogen and blue hydrogen are produced by fossil fuel, i.e., they couldn’t meet the requirement of environmental goals. However, green hydrogen is produced by renewable energy, i.e., it has a better future outlook. The forms of energy needed to produce green hydrogen can be classified in four categories, namely thermal, electrical, photonic and biochemical. Thermal and electrical energy can be produced from renewable energies (e.g., solar, wind, etc.), or from recovered energy and nuclear energy. Photonic energy only can be derived from solar radiation. The biochemical energy is stored in organic substances that usually come from microorganisms, which can extract hydrogen from various substrates, or it can be chemically converted to thermal energy [1].

Water electrolysis is selected as the research object among the hydrogen production methods. The main reason is that it is clean enough. Its raw material is water, and products are hydrogen and oxygen, indicating that there are no pollutants involved in the whole production process. However, due to the high cost of water electrolysis, it is not affordable to make an industrial large-scale application at present.

Among various hydrogen transportation methods, gaseous transportation technology is relatively mature. It can be divided into long tube trailer transportation and pipeline transportation. Long pipe trailer transportation is suitable for small amount and short-distance transportation, while pipeline transportation is suitable for large amount and long-distance transportation. Although liquid hydrogen transportation has technical problems, it is more efficient and has good future development prospects.

Liquid hydrogen storage is selected as the research object among the hydrogen storage methods. The main reason for choosing liquid hydrogen storage is that its energy density is much higher than that of gaseous hydrogen storage method, which mean it has a much higher hydrogen storage capacity.

3. HYDROGEN PRODUCTION METHODS: WATER ELECTROLYSIS

Due to hydrogen’s unavailability in the nature, it is necessary to find an environmental friendly and cheap hydrogen production methods if one wants to use hydrogen as fuel [2]. According to the raw materials, hydrogen production methods can be divided into two categories. The methods in the first category produce hydrogen from fossil fuels, including hydrocarbon reforming and pyrolysis. The methods in the first category produce hydrogen from renewable resources, either from biomass or water [3]. Figure 1 shows the various pathways for hydrogen production.
Figure 1. Hydrogen production methods [3]

Water electrolysis is a hydrogen production method, which belongs to the second category of hydrogen production methods. It splits water into hydrogen and oxygen under the influence of direct current. The electrons are taken and released through the ions at the electrodes surface when during the water electrolysis process, which lead to a multiphasic gas–liquid–solid system. The oxidation half-reaction occurs at the anode and the reduction half-reaction occurs at the cathode. The electrons leave the anode to the outside circuit, then the electrons are taken to the cathode from the outside circuit. Therefore, oxygen is generated at the anode and hydrogen at the cathode [4].

Here is the reaction formula of the water electrolysis:

Anode: $\text{H}_2\text{O} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^-$

Cathode: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$

Overall: $\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2}\text{O}_2$

During the electrolysis process, the electrolyte cannot react with the electrodes, otherwise the chemical composition of the electrolyte will change. Therefore, the electrodes should be resistant to corrosion. Besides, in order to make the electrolysis process more efficient and quickly, it is important for the electrodes to have a good electric conductivity and catalytic properties. In addition, one also needs a separator or diaphragm to prevent the recombination of the hydrogen and the oxygen generated at the electrodes. The electrical resistance of the separator also avoids short-circuiting the system. The separator should be easy for ion to conduct with high physical and chemical stability [4].

Among all the hydrogen production methods, water electrolysis is the most environmentally friendly way since neither its raw materials nor its byproducts would damage the environment. Nevertheless, the cost of this method is still high, which limits its large-scale generation. For example, the investment cost of the alkaline water electrolysis is estimated to be in the range of 1000–5000 $/kW depending on the production capacity [5]. Contemporarily, water electrolysis still cannot be applied in commerce, although it is technologically simple and environmentally friendly. The main reason is that it has a low energy efficiency. Its electrolyzer’s total efficiency is often less than 40 percent [6]. Besides, electricity is the most expensive form of energy, which only has an average efficiency of about 30 to 40% compared to primary energy [6]. In fact, many scholars have declared that hydrogen would become an important energy commodity in the future market, hence it is necessary to improve the performance and reduce the cost in production, storage, and conversion in hydrogen production [7].

In China, there are a large number of wind and solar power not used every year. According to the data from National Energy Administration, the surplus unused wind power in China was $497 \times 10^8$ kwh in
2016, when the total wind power was $2410 \times 10^8$ kWh. That mean almost 20.6% of the total energy produced would be wasted if we don't convert it into other forms of energy and store it [8]. Due to the transient characteristics of renewable energy sources (e.g., wind energy and solar energy), appropriate energy management and storage are required. Therefore, storing surplus renewable energy as hydrogen through water electrolysis shows great prospect [9].

There are different electrolytes systems for water electrolysis, including proton exchange membranes (PEMs), alkaline water electrolysis (AWE), solid oxide water electrolysis (SOE), and alkaline anion exchange membranes (AEMs). Although they use different materials and different operating conditions, they have the same operating principle [9]. The process of water electrolysis is schematically illustrated in Figure 2.

**Figure 2.** Water electrolysis process [9]

### 4. HYDROGEN TRANSPORTATION METHODS

Hydrogen transportation is divided into gaseous transportation and liquid transportation. Gaseous transportation includes pipeline transportation and trailer transportation. Trailer transportation technology is relatively mature, which is often used for short distance and small amount hydrogen transportation. China’s hydrogen energy development is still in the initial stage and the hydrogen production scale is small. Therefore, hydrogen transportation in China is short in distance and quantity. Trailer transportation is popularly used in China hence. Pipeline transportation has the advantages of large hydrogen capacity, low energy consumption and low cost, but the facilities investment in the construction of the pipeline is large, which is not suitable for the transportation mode in the early stage of hydrogen energy development. At present, the United States has 2500 km of hydrogen transmission pipeline and Europe has 1598 km of that, while China has only 100 km of that. In fact, one can try to transform the existing natural gas pipeline for hydrogen transportation. Cryogenic liquid hydrogen transportation has large hydrogen transportation capacity, which can reduce the frequency of vehicle transportation and improve the supply capacity of hydrogenation stations. It is suitable for long distance and large volume transportation. However, liquid transportation technology is difficult and facilities investment cost is high. Reducing the cost of hydrogen liquefaction and improving the thermal insulation performance of hydrogen storage containers are the key directions of research [10]. All the hydrogen transportation methods and their features are listed in Table I.

| Methods of Transportation | Features |
|--------------------------|----------|
| Gas                      | relatively mature, for short distance and small volume, popularly used in China |
| Pipeline                 | large capacity, low energy consumption, low cost, large facilities investment |
| Liquid                   | cryogenic, large transportation capacity, for long distance and large volume, difficult technology, large facilities investment |
5. HYDROGEN STORAGE METHODS

Hydrogen storage methods didn’t have any revolutionary changes in this decade. Figure 3 exhibits the different hydrogen storage technologies and their classification. By examining how hydrogen is changed in the storing process, researchers can distinguish the storage method a physical-based one or a material-based one. Physical storage methods include compressed gas storage, liquid storage and cryo-compressed storage, which depends on the change of storing conditions. Material-based, or solid state, storage methods include absorption or adsorption technique [11].

![Figure 3. Hydrogen storage technologies [11].](image)

Among the physical storage methods, High pressure storage is the most accomplished one. In fact, high pressure storage technology is utilized by nearly 80% of hydrogenation processes all over the world in hydrogen transportation and storage fields [12]. In CGH₂ methods, the internal pressure of the vessel is up to 70 MPa when hydrogen stored in [13]. The hydrogen density at this time is 40 g/L and the energy volumetric density is 1.32 kWh/L. In the process of hydrogen pressurization, about 10% of the gas energy content needs to be consumed [14]. However, high development and manufacturing costs are its main disadvantages [15]. Liquid hydrogen storage is to store hydrogen in the liquid state. It will be discussed in another section below. The density of hydrogen at high pressure (70 MPa) and room temperature is 39.1 kg/m³ while at low pressure (0.4 MPa) and low temperature (20 K) the density is 71.0 kg/m³. Whereas, gaseous hydrogen at high pressure and low temperature can have higher density even than liquid hydrogen, which can be up to 71.5kg/m³ [16]. Therefore, compared with LH₂, CcH₂ consumes less energy during compression. Compared with CGH₂, CcH₂ have higher energy volumetric density, but CcH₂ is seriously affected by heat leakage, and its pressure vessels is easy to deteriorate [16].

Generally, there are several shortcomings of physical storage, e.g., high energy consumption, low storage capacity, high demand for pressure resistance and heat insulation of vessel materials. When the vessel deteriorates, safety accidents may also occur, e.g., leakage, burst and fire hazards [11]. Therefore, one needs material-based storage to solve these problems. The storage materials of material-based storage should have certain characteristics, e.g., good reversibility, affordable price, rapid kinetics and high storage capacities [11]. Compared to physical storage, material-based storage is safer because of lower storing pressure and slower hydrogen release speed and has higher hydrogen storage capacity.

6. LIQUID HYDROGEN STORAGE

Liquid hydrogen storage (LHS) means that hydrogen can be cooled to -253.0°C to make it liquid and stored in a high vacuum insulated container. The critical point of \( \text{H}_2 \) occurs at temperature of \(-239.96 \degree \text{C}\), pressure of 1.3 MPa, and critical density of 31.43 kg/m³ [17]. Figure 4 is the Schematic route of \( \text{H}_2 \) storage/transportation through liquid \( \text{H}_2 \):
Although LH₂ (liquid hydrogen) is similar to LNG (liquid natural gas), there are still some technical challenges in LHS since the boiling point of LH₂ is much lower than LNG and the storage temperature is about 90°C lower. Liquefaction can be performed at the H₂ production site or port facility before being transported in order to integrate H₂ production and liquefaction to reduce the cost [19]. One of the main barriers in H₂ liquefaction is high-energy consumption. Nearly one-third of the produced H₂ is supplied to it [20]. Besides, Large-scale H₂ liquefaction is generally performed by employing a refrigeration cycle, and throttling is performed by changing the pressure, including the processes of compression and expansion. such as Claude, Kapitza, Joule-Brayton, helium pre-cooled Claude, and pre-cooled Linde-Hampson [21].

There are several factors that would be influential to the process of storage: heat leakage, ortho-para conversion, sloshing, and flashing. During storage and transportation of liquid H₂, a boil-off of about 0.2%–0.3% LH₂ per day may occur [22]. One solution of it is to develop more excellent thermal insulation technology, usually adopting vacuum thermal insulation, which could reduce energy loss through heat leakage. The other way is to reduce sloshing in the transportation by utilizing anti-slosh baffles, which could reduce the additional heat generated by sloshing. During storage or transportation, the management of boil-off is important for the pressure controlling in the vessel, for boil-off can increase the pressure inside the vessel. When the pressure inside the vessel increases to the threshold value, the blow-off valve must be opened to release the hydrogen gas. There are several methods that can reduce hydrogen loss caused by boil-off, such as the integration of refrigeration systems or cryocoolers, passive insulation, combination with metal hydrides, and liquid nitrogen cooling [18].

Liquid H₂ requires regasification before being utilized. During the regasification process, the cold energy of LH₂ can be recovered, which would increase the energy efficiency in the utilization site. The recovery of cryogenic exergy has been applied in LNG regasification systems. However, as liquid H₂ has a lower temperature than LNG, as well as other conditions, the system needs to be re-developed and improved [18]. Regasification and utilization can be combined (e.g., power generation), which can make a higher total energy efficiency. Besides, since the liquid hydrogen has high purity, it should be applied to systems demanding high H₂ purity, e.g., fuel cells for power generation and H₂-based vehicles.

The energy efficiency of LHS is about 40%–50%. Hydrogen production’s energy efficiency is 50%–70%, while that of transportation and utilization is about 95% and 50%–70%. LHS has a high H₂ volumetric energy density which is about 800 times of volumetric H₂ energy density. Its specific number is 2360.97 kW h/m³. It can save a large part of space in storage and transportation. During storage and transportation of liquid H₂, a boil-off of about 0.2%–0.3%/d may occur. The ratio of evaporation to total amount decreases with the increase of vessel size. Consequently, the lifetime of LHS is only about 300-500 days. According to the forecast, if we assume that H₂ is produced in Australia and transported to Japan, the cost of hydrogen storing in the liquid state will be 35.8 JPY·Nm⁻³ in 2030 and 24.34 JPY·Nm⁻³ in 2050 in Japan [18].

Table II shows the advantages and disadvantages of LHS. Compared with other hydrogen storage methods, LHS has higher hydrogen purity. The hydrogen stored in this way can be used in cases where there are high requirements for hydrogen purity. In addition, LHS is a physical storage method. Therefore, LHS requires no dehydrogenation and purification. The second advantage of LHS is that the volumetric energy content of liquid hydrogen is much higher than that of compressed hydrogen gas at room temperature, which means that it can store more hydrogen in a smaller space. This also makes the transportation of liquid hydrogen more efficient. As mentioned in the section “hydrogen transportation...
methods”, liquid hydrogen storage containers are suitable for long-distance and large equivalent transportation. Finally, the security of LHS is relatively good [18, 23].

The most serious shortage of LHS is that it consumes a lot of energy during liquefaction, as almost one-third of the produced H2 is supplied to cover it. This is a waste of energy, which leads to the high cost of LHS. In addition, LHS requires a very low temperature (about -250 °C). Thus, compared with other storage methods, it is necessary for LHS to develop vessel / technologies in order to make it work at low temperature. Besides, because LHS loses 0.2% - 0.3% hydrogen every day, it is difficult to store hydrogen for a long time. Finally, LHS also has the risk of hydrogen leakage [18, 23].

| TABLE II. THE ADVANTAGES AND DISADVANTAGES OF LHS |
|-----------------------------------------------|
| Advantage                                      | Disadvantage                                      |
| 1. High purity                                 | 1. High energy consumption for liquefaction       |
| 2. No dehydrogenation and purification         | 2. Requirement for vessel / technologies in low temperature |
| 3. High volumetric energy density              | 3. Difficult for long term storage                |
| 4. Relatively good security                    | 4. Risk of leakage                                |

7. FEASIBILITY STUDY

7.1 Feasibility study of water electrolysis

Previous literature demonstrates typical characteristics of the main electrolysis technologies, where different water electrolysis technologies have different commercial feasibility (applicability) [24]. AWE is relatively mature and has already been commercially available. PEM is commercially available for low-scale applications, but some technical problems still have not been solved. SOEs are at the R&D stage, with only laboratory-scale application and demonstration.

AWE is the most mature one among all electrolysis technologies. Nowadays, it is the most extended technology at a commercial level worldwide [4]. Alkaline water electrolyzers are reliable and safe, with energy efficiency in the range of 47%–82%. Their lifetime can reach up to 15 years [25]. The investment costs vary according to production capacity, which is calculated to be in the range of 1000–5000 $/kW [26]. At present, AWE is the most feasible technology for large-scale commercialization. However, as alkaline electrolyzers’ start-up speed is slow, it is hard to adapt to the variable nature of renewable energy sources [27]. In the long run, AWE does not quite match this research’s sustainability goal.

PEM electrolysis have the advantages of fast start-up and response, compact design, high efficiency, and high output pressure. These make PEM have a good developing outlook. Besides, compared with AWE, PEM electrolysis don’t generate alkaline fog, which mean the latter one is more environmental friendly. PEM has high commercial feasibility in the future. However, current PEM electrolyzers’ limited production capacity, short operation life and expensive investment cost make few companies are willing to produce it. Therefore, PEM electrolysis is commercially available for only small-scale applications. Its commercial feasibility is not good at present.

High temperature solid oxide electrolysis (SOEC) is considered as an advanced concept as its energy efficiency is higher than that of AWE and PEM electrolysis [28]. However, there are still challenges in SOE technologies, such as Material degradation in high temperature and limited long-term stability of the electrolysis cells [28]. SOE technologies are still under research and development, which will take a long time until SOEs are commercially available.

7.2 Feasibility study of liquid hydrogen storage

Liquid H2 has been practically adopted and commercially available for a long time. Storing hydrogen in liquid state is one of the most feasible options of hydrogen storage. In fact, the hydrogen liquefaction capacity provided by current infrastructure is much lower than that required for powering the transportation sector, especially the road transportation. An infrastructure greater than the current one by
at least two orders of magnitude is required. Further development and construction for large-scale infrastructure is needed [23].

The biggest drawback of LHS method is the high energy consumption during liquefaction, which results in higher cost than other storage methods. Based on Linde and Praxair plants, industrial large-scale H₂ liquefaction consumes about 13–15 kWh/kg at present (about 40% of the LHV of H₂) [21]. Latest research results were able to reduce the energy consumption to 4.3–10.8 kWh/kg. It is predicted that on a very large scale, the energy consumption of H₂ liquefaction can be further decreased to about 7.5–9.0 kWh/kg (about 22–27% of the LHV of H₂) in the future. Another point that has a negative impact on the feasibility of LHS is that there is no commercially available tanker for large-scale LH₂ transportation currently [29].

8. CONCLUSION

In summary, there are two sustainability goals in this study: environmentally and economically. Environmentally, human beings need to find suitable clean energy to eliminate the emission of pollutants and greenhouse gases. Economically, new energy technologies should be invested if it is affordable, accessible, and cost-effective.

Based on raw materials, the hydrogen production methods are divided into two categories: fossil fuels and renewable sources. Water electrolysis belongs to the second category, which is a zero-carbon emission process. It is environmentally friendly enough as its raw material is water and byproduct are hydrogen, but the cost of this method is expensive. Among the hydrogen transportation methods, gaseous transportation technology is more mature. Though liquid transportation has technical problems, it still has a bright future.

Hydrogen changes differently in different storage methods during storage process. Hydrogen storage methods can be divided into two categories: physical storage and material-based storage. LHS is a physical storage method, which is introduced in detail with several crucial data including its energy efficiency, energy density, lifetime, cost and response time. LHS’s advantage include high purity, no dehydrogenation and purification, high volumetric energy density as well as good security. Its disadvantages include high energy consumption for liquefaction, requirement for vessel/technologies in low temperature, difficult for long term storage, risk of leakage.

The feasibility study of water electrolysis and liquid hydrogen storage is combined with sustainability goals. Among the electrolysis technologies, AWE is the most mature one and has the best commercial feasibility at present. Nevertheless, its future potential may not as good as PEM electrolysis and SOEC. PEM electrolysis is only small-scale commercially available. Even though, it has higher commercial feasibility than AWE in the future. SOEC is an advanced concept, but there are a lot of challenges before it is feasible in commence.

LHS is one of the most feasible options of hydrogen storage since there is a large gap of demand for hydrogen energy in road transportation. In the future, the energy consumption of liquefaction will decrease from 13–15 kWh/kg to 7.5–9.0 kWh/kg. With the reduction of energy consumption during liquefaction and the development of commercially available tank for large-scale LH₂ transportation, LHS will have better and better feasibility.

Hydrogen energy is an important direction of the global energy technology revolution. It will be an essential part of sustainable and clean energy in the future. It is hoped that this feasibility study of hydrogen generation and storage will be helpful to the realization of sustainability goals, offer some useful information for correlative research and provide more references for the government to formulate policies related to hydrogen.

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