THE OPTIMIZATION OF PROTON EXCHANGE MEMBRANE HYDROGEN FUEL CELLS

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Abstract—The development and widespread use of proton exchange membrane fuel cells (PEMFCs) in the transportation industry has the potential to minimize CO₂ emissions and consequently global warming effects. Among the detrimental effects of excess CO₂ emissions include increase in average temperatures, extreme weather events, ocean acidification, glacial retreat, and animal extinction. As the technology continues to develop, fuel cells will be able to completely replace petroleum fuel, which is used in most automobiles today, and power nearly any device that currently uses batteries.

In this paper, we will investigate PEMFCs, specifically hydrogen fuel cells. A major focal point is an in-depth description of how the technology functions. This section will include an explanation of the oxidation reduction reaction and the role of the cathode, anode, catalyst, and electrolyte in a fuel cell. Another focal point in this paper is the optimization of hydrogen fuel cells. Within this section of the paper, we will explore the use of different kinds of carbon supports for cathodes and anodes, specifically carbon nanotubes (CNTs) and ordered mesoporous carbons (OMCs), the use of water-based acids, proton exchange membranes, and molten carbonate as electrolytes, and evaluate platinum as a catalyst. In addition, we will also explore problems concerning the technology, including the production and storage of pure hydrogen and hydrogen’s violent traits.

Key Words—Electrolysis, Formic acid electrolyte, Hydrogen fuel cell, Mesoporous carbon supports, Oxidation reduction reaction, Platinum catalyst, Voltage Loss

IMPORTANCE AND SUSTAINABILITY OF HYDROGEN FUEL CELLS

Greenhouse Gas Emissions

The Union of Concerned Scientists (UCS) estimates the U.S. transportation sector, including cars, planes, trains, ships, and freight produces thirty percent of all U.S. global warming emissions [1]. Furthermore, nearly one-fifth of these emissions are produced by just cars and trucks, which alone combine to emit about 24 pounds of carbon dioxide for every gallon of gasoline [1]. Among the detrimental effects of excess CO₂ emissions include the increase in average temperatures, extreme weather events, ocean acidification, glacial retreat, and animal extinction [1]. The consequences become more grave as the air pollutant and greenhouse gas concentrations in the atmosphere continue to rise, making the issue a top priority for scientists and engineers.

Renewable resources

The United States is undergoing an energy transformation led by renewable energy sources such as biomass, hydropower, geothermal, wind, and solar. The U.S. Energy Information Administration (EIA) reports the usage of these energy sources more than doubled from 2000 to 2015 [2]. Furthermore, renewable energy produced 10% of the total United States’ energy consumption in 2015 and a 13% growth in renewable energy sources between 2015 and 2021 is projected [2]. These energy sources do not directly produce greenhouse gases and play a critical role in reducing greenhouse gas emissions.

Among these renewable energy sources are proton exchange membrane fuel cells (PEMFCs), which converts chemical potential energy into electricity. This paper will focus specifically on the optimization of proton exchange membrane hydrogen fuel cell components. According to National Geographic, fuel cells will eventually completely replace petroleum fuel, which is used in most automobiles today, and power nearly any device that currently uses batteries [3]. Like many of the other renewable energy sources, a hydrogen fuel cell emits only water, electricity, and heat [3].

Hydrogen Fuel Cell Sustainability

It is clear that massive amounts of money and research have been invested in renewable energy sources. Engineers and scientists have been working to improve upon “sustainability” in the U.S. energy industry, as a large majority of the country’s energy is produced using fossil fuels. As defined by the United States Environmental Protection Agency (EPA), “To pursue sustainability is to create and maintain the conditions under which humans and
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nature can exist in productive harmony to support present and future generations” [4]. Of course, a technology’s sustainability is a combination of many variables, which also includes cost.

There is considerable evidence that the sustainability of fossil fuel energy production is not limited by the amount of fossil fuel reserves in the world. Instead, it is dependent on humans and nature’s ability to adapt to the consequences of greenhouse gases. It is clear that many struggling ecosystems, such as coral reefs, have failed to adjust to the increased water acidification and temperature. These ecosystems, as well as weather patterns and ocean acidity levels can all be sustained by replacing fossil fuels with hydrogen fuel cells. Hydrogen fuel cells’ byproducts include water and heat, which both pose no harm to the humans or animals. As a result, not only are the ingredients of hydrogen fuel cells abundant, but the technology is also environmentally friendly for posterity.

One of the reasons renewable energy sources are not more widespread is their cost. Therefore, decreasing the cost of renewable energy sources such as hydrogen fuel cells is an effective way of increasing their sustainability. This is largely due to the catalyst, platinum, which does a good job for its role within the cell, but is an expensive metal.

There are four main components to a hydrogen fuel cell: anode, cathode, electrolyte, and catalyst. The placement of each of these components are illustrated in Figure 2. In order for a PEMFC to produce energy, it must undergo an electrochemical process called an oxidation reduction reaction. An external source of fuel, which is hydrogen in this case, and an oxidant, such as oxygen are utilized [5]. Oxygen is readily available from earth’s atmosphere and hydrogen can be produced through electrolysis, which will be explained in detail later in this paper. As hydrogen molecules are pumped into the device on the anode side, they are ionized into hydrogen protons and electrons [5]. This oxidation reaction is aided by the anode and its catalyst, which is typically made of platinum nanoparticles [5]. The catalyst accelerates the reaction and lowers the activation energy necessary for the reaction to occur [5]. Located in between the positively charged cathode and negatively charged anode is a proton exchange membrane, which only allows hydrogen protons to flow [5]. Meanwhile, the electrons are forced to take an alternate route through a circuit, creating electricity [5]. After the electrons and protons have finished their route around the anode, they both reach the cathode, where oxygen is supplied [5]. The oxygen molecules undergo a reduction reaction that utilizes the hydrogen protons and electrons from the anode reaction, forming water vapor and heat [5].

Anode side (oxidation reaction):

$$2 \text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^-$$

Cathode side (reduction reaction):

$$\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$$

Net reaction

$$2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$$

**FIGURE 1[3]**

The oxidation-reduction reaction between the cathode and anode, leading to electricity production

**DESCRIPTION AND OPTIMIZATION OF HYDROGEN FUEL CELL COMPONENTS**

**Basic Overview of Hydrogen Fuel Cell**

Because a single hydrogen fuel cell such as one shown in Figure 2 has a very low potential (about 0.6 - 0.7 V), it produces power at a very slow rate [4]. Manufacturers must combine many hydrogen fuel cells in series, or a stack (Figure 2), in order to produce enough power for the technology to realistically be used on a day-to-day basis, such as in a vehicle [6]. Between the anode of one cell and the cathode of an adjacent fuel cell is a bipolar plate, which plays an integral role in the fuel cell function. According to the *International Journal of Hydrogen Energy*, the bipolar plate is responsible for supplying reactant gases through flow channels to each electrode and electronically connecting each cell [7]. It also provides overall structural support for the system and is involved in the processes that manage heat and the flow of waste water within the cell [7]. The characteristics of an ideal bipolar plate include high electronic conductivity and resistance to corrosion and impermeability to reactant gases. [7].
The power produced is also directly proportional to the current that flows through the system. The current that flows through a hydrogen fuel cell can be increased by maximizing the surface area of the electrodes [5]. This allows the maximum number of hydrogen molecules coming into contact with the catalyst at the anode, which increases the number of oxidation reactions. This will be discussed in depth later in this paper.

Contrary to an ideal fuel cell, the voltage and current in a real fuel cell are dependent on each other. According to a study published by Springer Verlag, the increased current in a fuel cell contributes to voltage losses which significantly impact the power produced by the cell [8]. Although these voltage losses have many sources, they can be generalized into activation losses, concentration losses, and ohmic losses [8]. Figure 3 reveals the amount of voltage due to each of these sources in a hydrogen fuel cell.

**Figure 3 [6]
Diagram of a series of three hydrogen fuel cells connected with bipolar plates**

**VOLTAGE LOSSES**

**Activation Losses**

As previously mentioned, initiating the redox reaction requires an activation energy, which is provided at the expense of voltage [8]. This activation loss is continuously occurring in a fuel cell to maintain a desired speed or power output. Since the rate of reaction at the cathode is much slower than the rate of reaction at the anode, the activation losses at the cathode are much greater than the activation losses at the anode [8]. Therefore, the voltage loss is proportional to the speed of the reaction, which is determined by the current in the system. This relationship is given by the following Tafel Equation:

\[ \Delta V = A \ln \left( \frac{I}{I_0} \right) \]  

(1)

where \( A \) is a constant that is dependent on the catalyst material and reactant composition and \( I_0 \) is the exchange current density [8]. Minimizing the activation losses can be achieved by increasing operational temperature, which increases the exchange current density, increasing catalytic efficiency and presence and operational pressure, which all increase the rate of reaction, and using more effective cathode materials [8].

**Mass Transport/Concentration Losses**

The consumption of reactant gases at the anode and cathode form concentration gradients, which decrease the partial pressure of the reactants and consequently decreases the fuel cell voltage [8]. If hydrogen is added at a high rate on the anode electrode, the partial pressure of hydrogen drops, slowing the reaction rate, which in turn forces more voltage to be used to overcome the activation energy [8]. The same effect occurs on the oxygen at the cathode. As a result, mass transport losses increase greatly with an increase in current [8].

**Ohmic Losses**

Ohmic losses are due to the total electrical resistance of the system, which is provided at the expense of voltage. Different methods used to reduce ohmic losses include maximizing electrode and bipolar plate electrical conductivities and reducing the thickness of electrolytes [8]. Although these losses are relatively small compared to the other losses, ohmic losses remain an issue in hydrogen fuel cells.

\[ \Delta V = i r \]  

(2)

where \( i \) is the current density and \( r \) is the area-specific resistance. Different methods to reduce ohmic losses include maximizing electrode and bipolar plate electrical conductivities and reducing the thickness of electrolytes [8]. Although these losses are relatively small compared to the other losses, ohmic losses remain an issue in hydrogen fuel cells.

**OPTIMIZATION OF CATALYST**

In order to accelerate the oxidation reaction at the anode and reduction reaction at the cathode, a catalyst, usually
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Platinum (Pt), is placed in the form of small particles on the electrodes. According to Johnson Matthey, a specialty chemicals and sustainable technologies company, the hydrogen oxidation reaction at the anode with a Pt catalyst occurs very quickly, causing an activation voltage loss of less than 5 mV [9]. The oxygen reduction reaction at the cathode, however, is much more complicated and is five times slower. As a result of the kinetics of the reaction, the cathode requires several times the amount of Pt catalyst on the anode.

Creating the right catalyst for the cathode is currently a major problem in hydrogen fuel cells because it must be able to resist corrosive conditions while still being chemically active enough to react with oxygen [9]. This catalyst must also be able to release waste water from the catalyst surface to give the oxygen flow more area to react [9]. Since the overall rate of power production in the fuel cell is directly correlated to the catalyst efficiency, creating the optimal catalyst is a major focus for many researchers. They judge catalysts using three main criteria: activity, selectivity, and stability [9].

**Activity**

A catalyst’s activity describes its ability to adsorb the reactant strongly enough to break the initial chemical bonds, but also weak enough to allow the flow of products after the reaction has occurred [9]. A catalyst that reacts too strongly with its reactants would cause the surface of the catalyst to become crowded and prevent any flow of gas from reacting [9]. On the other hand, a catalyst that reacts too weakly with its reactants would not be able to bind to enough reactants [9]. In both cases, the rate of reaction decreases and overall fuel cell efficiency decreases.

This idea of having optimal interaction between the catalyst and reactant in a fuel cell is called the Sabatier principle [8]. This concept in fuel cells is best represented by the Balandin volcano diagram in Figure 5, which plots the logarithm of exchange current density versus the adsorption energy strength [9]. Figure 5 reveals a clear activity peak with optimal binding, which is most closely obtained by Pt.

**Selectivity**

A catalyst that has ideal selectivity minimizes the number of intermediates and unwanted waste products in the reactions at the anode and cathode [9]. The hydrogen oxidation has only one possible mechanism and therefore the selectivity does not affect the anode [9]. There are two possible mechanisms at the cathode for the oxygen reduction and the pathway taken is determined by the selectivity of the catalyst [9]. One pathway involves a four-electron oxidation reduction reaction mechanism that produces water and the other is a two-electron reaction mechanism that produces H$_2$O$_2$ [9]. To optimize efficiency in the fuel cell, the catalyst must favor the former reaction because H$_2$O$_2$ can be destructive when added to the cell environment [9].

The amount of H$_2$O$_2$ produced using a metal catalyst can be determined using scanning electrochemical microscopy. This technology is able to calculate $n$, the number of electrons transferred in the reaction [9]. The extreme values of $n=2$ and $n=4$ represent reactions producing only H$_2$O and only H$_2$O$_2$, respectively [9]. The graphs in Figure 6 show the mechanism preferred by several metal catalysts as a function of potential. The data suggests that platinum is the most effective catalyst with respect to selectivity [9]. It is nearly 100% selective towards H$_2$O production over a large potential range [9].
It is essential for a catalyst to respond well to the hostile chemical environment inside a fuel cell to ensure fuel cell durability [9]. A catalyst must be able to withstand the presence of strong oxidants, reactive radicals, low pH levels, high temperature and rapid potential changes inside a fuel cell [9]. The strong oxidant in a fuel cell is the hydrogen fuel and the reactive radicals include the $\text{H}^+$ and $\text{OH}^-$ ions, which result from the redox reaction. This limits the number of choices for catalysts because very few metals can resist dissolution, or breaking down, at low pH and high potential levels [9]. In addition, many metals that would be stable in these conditions hold an oxide film that helps prevent dissolution, but are also counterproductive because the film also inhibits the reaction at the cathode [9]. The Pourbaix diagrams shown in Figure 7 and 8 illustrate how different metals react to varying pH and potential levels. As revealed from the data, noble metals such as gold, iridium, and platinum remain the most stable despite significant changes in the environment.

FIGURE 6 [9]
A comparison of selectivity of several pure metals

Stability

It is clear that Pt is the most efficient pure metal catalyst as it ranks near the top at each of these three criteria. However, the reaction at the cathode remains slow and consumes large

FIGURE 7 [9]
Figure 7 contains a legend for different kinds of responses metals might have as the conditions change

FIGURE 8 [9]
Compares the stability of different metal catalysts using legend from Figure 7

Platinum Alternatives

It is clear that Pt is the most efficient pure metal catalyst as it ranks near the top at each of these three criteria. However, the reaction at the cathode remains slow and consumes large
amounts of energy. [9]. Pt does not sit at the peak activity level in the Balandin volcano plot, suggesting that the ideal catalyst would have slightly different properties [9]. To further optimize hydrogen fuel cells’ efficiency, research is being conducted on creating a catalyst that excels at each requirement. Some research ideas that might improve Pt’s activity include alloying with other metals, layering with another metal, and using a core-shell approach that would coat a cheaper metal with Pt [9]. The alternative must also be able to match Pt’s performance in each of the other two criteria as well. The following section will consider the reaction from the perspective of the cathode and explore optimal materials.

CATHODE OPTIMIZATION

According to a study published by the University of Calgary, hydrogen fuel cells currently use microporous carbon supports as the catalyst cathode layer in order to allow small platinum nanoparticles to attach to the large surface area of the cathode [10]. The typical material used for this component is Vulcan Carbon XC-72R (VC), which was chosen because of its good conductivity properties and good chemical and physical cleanliness [10]. Despite this, VC does a poor job of accommodating its platinum catalyst compared to mesoporous carbons [10]. VC pores are too small to effectively hold platinum nanoparticles, which allows only a fraction of the electrode’s surface area to contribute to the catalytic reaction [10].

Researchers have been researching mesoporous carbon support materials that would have larger pore diameter and surface to improve platinum distribution, [10]. Two specific mesoporous carbon support materials that have shown promise as cathode materials include carbon nanotubes (CNTs) and ordered mesoporous carbons (OMCs) [10].

Carbon Nanotubes

A Carbon Nanotube (CNT) is a seamless cylindrical-shaped material made of a single sheet of pure graphite, which consists of a hexagonal lattice of carbon [10]. The carbon atoms form a planar honeycomb lattice in which each carbon is bonded strongly with three adjacent atoms [10]. Its structure allows them to obtain extraordinary properties such as thermal and electrical conductivities higher than copper and strength and elasticity superior to steel [10]. The use of CNTs for the cathode catalyst layer offers many advantages over the use of VC. For instance, CNTs’ 100% sp\(^2\) hybridization allows them to have a higher electronic conductivity than VC, allowing electrons to flow through the cell faster and increasing energy output [10]. This hybridization also contributes to the material’s corrosion resistance [10]. CNTs also generally produce less unwanted waste compared to VC, which often contain sulfur species that can be damaging to the Pt catalyst [10].

Despite the benefits that accompany CNTs’ sp\(^2\) hybridization, this hybridization also causes a lack of functional groups, areas where the platinum nanoparticles can attach [10]. A possible solution to this issue involves a reflux process that forms hydroxyl and carboxylic acid surface groups [10]. Unfortunately, this decreases the CNTs’ electronic conductivity and balance must be created between the material’s electronic conductivity and platinum distribution and stability to find the best combination.

Ordered Mesoporous Carbons

Another type of mesoporous carbon support that is actively being researched is the Ordered Mesoporous Carbons (OMC). Their small pore sizes and high surface areas allow them to be effective catalysts in many adsorption technologies, such as cathode catalysis layers [11]. This material, however, suffers from a lack of functional groups, similar to CNTs [11]. Generally, this material can be functionalized through oxidation treatments while maintaining all the desired properties of OMCs. Treatments using strong oxidizing agents such as nitric acid form a high concentration of oxygen groups at the cathode surface whereas weaker oxidizing agents such as sodium hypochlorite and hydrogen peroxide form phenol groups [11]. Additionally, the large surface area of OMCs (2000 m\(^2\)/g) in combination with small pore sizes allow more platinum nanoparticles to attach than to VC (1500 m\(^2\)/g) does [10].

The disadvantage of using the OMCs is that efficiency is limited by high current density due to mass transport voltage losses [10]. Because of this, OMC catalyst layers are more efficient than VC catalyst layers at low current densities, but are overcome with large energy losses as the current density increases [10]. In order to reduce these losses, the material must be engineered to contain larger pore sizes, which is difficult to achieve without completely changing many of the material’s properties [10].

A depiction of a graphene sheet and the carbon nanotube that it forms
OPTIMIZATION OF THE ELECTROLYTE

The flow of hydrogen in a hydrogen fuel cell splitting into its hydrogen proton and electron components implies the use of an electrolyte somewhere along the process. An electrolyte is a compound that ionizes into a positively charged ion and a negatively charged ion when put in water. The positive and negative ions allow electricity to be transmitted from one atom to the next and eventually, the whole solution. Any compound can be considered an electrolyte if it ionizes in water, however the efficiency of the electrolyte is determined by two factors. The first is the percentage of ionization. Strong electrolytes ionize 100% into their components while weak electrolytes do not. There are only two types of compounds that can completely ionize: acids and bases. If an acid or base ionizes completely, it is called a strong acid or strong base. The second factor that determines the electrolyte’s efficiency is the concentration of the solute in water.

The Journal of Membrane science states that the main requirements of a favorable fuel cell membrane include high proton conductivity, low water permeability, good mechanical and thermal stability, and moderate price [14]. Several kinds of electrolytes include proton exchange membrane (PEM), water-based acids, and molten carbonate [15].

Proton Exchange Membrane (PEM) Electrolyte

A proton exchange membrane (PEM) is generally made of ionomers, a type of polymer comprised of electrically neutral molecules bonded to a fraction of ionized molecules [15]. This arrangement creates a semi-permeable membrane that only allows protons to pass through. Since the hydrogen fuel cell operates on the flow of electrons, which will be used to create electricity, it makes the proton exchange membrane the ideal fit [15]. This is because the electrons need to flow through the circuit to power the device connected. The only byproduct of the fuel cell reaction is water and it is imperative that the electrolyte does not allow water to permeate through because the unwanted water can be damaging to the efficiency and overall health of the cell.

PEMs also require no liquid, which is beneficial because they cannot leak like many other electrolytes. The electrolyte’s efficiency ranges from only 40% to 50%, but operates at 80°C, which makes them a safe choice for houses and cars [14]. The thickness of PEMs can also affect the efficiency of the fuel cell because a thicker membrane will have a larger resistance and consequently less energy would be produced [14]. The PEM performs well in each of the requirements that define a favorable cell membrane. For this reason, it is currently the most common and more efficient electrolyte for hydrogen fuel cells [15].

Water-based Acids and Molten Carbonate Electrolytes

Two other electrolytes are water-based acids and molten carbonates [14]. Water-based electrolytes have an efficiency of 40 percent to 80 percent and operate at temperatures between 150°C and 200°C, according to the Smithsonian Institution [14]. Molten carbonate ionizes in water to create an electrolyte with an efficiency of about 60 percent to 80 percent [14]. This electrolyte operates at 650°C, a much higher temperature than water-based acids [14]. Molten carbonate’s high operating temperature prevents its use in houses and cars due to safety option reasons, but it can be implemented into other technology such as spacecraft or submersibles.

FLEMION, NAFION, AND ACIPLEX PROTON EXCHANGE MEMBRANES

As in all processes, there are many ways to accomplish the same task. PEMs are no exception. Examples of commercially available PEMs are Flemion, Nafion, and Aciplex. These are composed of similar materials but have distinct properties. Ashashi Glass Company, the distributor of Flemion, states that it is a fluoropolymer that was originally produced to reduce the pollution of caustic soda (Sodium Hydroxide) production [16]. Since Flemion is a fluoropolymer, the ionized molecules bonded to the polymer are fluorine atoms [16]. The Royal Society of Chemistry states that Nafion uses a Teflon backbone as its polymer and bonds to a Sulfonic Acid group [17]. Aciplex was created for a similar reason as Flemion and is made of the same structure, fluorine bonded to a polymer [16].

Nafion, Flemion, and Aciplex Comparison

There has been the most research done on Nafion PEMs because they are very stable, have high ionic conductivity, and have good mechanical strength [17]. A study was published by the Royal Society of Chemistry comparing the three PEMs [17]. The tests were performed by using different thicknesses of each of the three types and comparing the two
closest thicknesses of the Aciplex and Flemion to Nafion [17]. That proved that the Nafion and Aciplex perform very similarly in terms of current density and the cell’s potential (See Figure 10). This experiment also reveals that Flemion outperformed Nafion in long term stability for the cell potential over the current density (See Figure 11). In terms of use, the Flemion would be the most efficient because of its long-term stability. Flemion’s performance can be attributed to its low resistance, which allows it to be the most energy efficient (See Figure 11). The electrical current efficiency is around 97% continuously [17].

Figure 10 [17]
A comparison of the efficiency of Nafion (50 μm) to Aciplex (50 μm)

Figure 11 [17]
A comparison of the efficiency of Nafion (88 μm) to Flemion (80 μm)

PROBLEMS WITH HYDROGEN FUEL CELLS

Mass Production of Hydrogen

The only fuel required to power a PEMFC is the air we breathe and pure hydrogen. Air is readily available and requires no need for storage in compressed tanks because the design of the fuel cells allow air flow. On the other hand, the acquisition of hydrogen can be a long process. Although hydrogen makes up 75% of the universe, hydrogen in its raw form exists only at the outside of our atmosphere due its density. Hydrogen is 2 times lighter than helium and 14 times lighter than air (made of Nitrogen, Oxygen, Argon, and Carbon Dioxide), as Elmhurst College states [18]. A study at Harvard returned the amount of hydrogen present in the atmosphere as 531 parts per billions [19]. This means that for every billion molecules in the atmosphere, only 531 hydrogen molecules exist [19].

The Office of Energy Efficiency and Renewable Energy argues that the only foreseeable option that could produce mass amounts of pure hydrogen is electrolysis [20]. Electrolysis involves an electrical current that is run through two electrodes submerged in water. The cathode produces hydrogen gas and the anode produces oxygen [20]. The electricity splits the water into its two ions: H⁺ and O⁻² [20]. The charge of the hydrogen is positive, so it is attracted to the negative cathode and the negatively charged oxygen is attracted to the positively charged anode [20].
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Issues with Electrolysis

There are two main concerns with hydrogen production through electrolysis. The first is the cost. The cost of hydrogen ranges from $3.74 /kg to $5.86 /kg, while gasoline costs $2.32 /kg [21,22]. Research is currently being conducted to create cheaper methods of producing hydrogen. For example, genetically engineering algae can be used to produce hydrogen, as found in a study published by Biotechnology and Bioengineering [23].

The second main concern is the electricity needed to power the electrolysis. Currently, the power comes from a regular power grid, which creates electricity by burning fossil fuels [20]. This makes the whole process counter-productive [20]. Research is currently being done to make use of clean energy sources in the hydrogen production process.

Vollatility of Hydrogen

The use of hydrogen to fuel cars or houses might be questionable considering its reputation of being a very volatile gas. However, the Hydrogen Association states that although hydrogen does have a low ignition temperature (500 °C), it is not much higher than that of gasoline (336 °C) [24]. Despite this, hydrogen will still ignite if it is near a flame with concentration of at least 4 [24]. This presents an even bigger issue if it is confined in a tank in the case of a car or house [24]. This combination is especially dangerous because there is an increased chance for a leak that would ignite with any spark or open flame [24]. There is, however, research published by International Journal of Hydrogen Energy about blowers, which can sense a hydrogen leak and disperse it to a concentration that is inflammable [25]. These blowers work very efficiently and can quickly and effectively bring the concentration down to a safe level as shown in Figure 13 [24].

![Figure 13](image)

**Figure 13 [25]** Illustrates the percent concentration of Hydrogen from a leak after the blowers were used

Storing Hydrogen

The final and most challenging issue with hydrogen fuel cells is the act of storing hydrogen. The first method is storing hydrogen as a gas. Earlier, it was stated that hydrogen is the least dense gas [18]. The actual molecule itself is only made of two protons and two electrons. This makes the particle extremely small. The Office of Energy Efficiency and Renewable Energy claims that these molecules are so small that any normal tank that is filled with a pressurized gas will cause a large hydrogen leak [26].

Hydrogen can also be stored as a liquid, which also gives way to a hydrogen leak with any crack or imperfection in the storage container [26].

The last way hydrogen can be stored is in a chemical compound [26]. Hydrogen can be made into sorbents and metal hydrides [26]. This solves the problem of the hydrogen leaking, but makes it difficult to separate the compound into pure hydrogen when it is needed. Methods to separate the compound include using another chemical or running a current through them [26].

**THE FUTURE OF HYDROGEN FUEL CELLS**

While the main focus of hydrogen fuel cells is their application in transportation, the Department of Energy Hydrogen Program states that they would also be viable energy sources for back-up power in houses or buildings, portable power, and small distributed generators [27].

Despite its problems, PEMFCs using hydrogen remains a very promising technology. There is research being done on all aspects of hydrogen fuel cells such as voltage losses, optimal catalyst, cathode, and electrolyte material, and hydrogen production and storage. It is clear that hydrogen fuel cells are still being developed and are not yet advanced enough to be mass produced. If a practical solution is created each of the issues listed in this paper, the technology is capable of revolutionizing the energy field.

In conclusion, it is clear that humans’ continued success and sustainability is largely dependent on their ability to adapt to the constantly changing environment. The innovation and application of efficient and renewable energy sources, such as hydrogen fuel cells, are imperative to reduce the damaging effects of fossil fuel greenhouse gas emissions.

**SOURCES**


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