Hydrogen Fuel Cells

CHEM 300A Project 1

University of Victoria

Prepared by

Jindian Eric He, Jon Gale, Kia Pezesh, Lagan Chohan, Milana Dintino, Trinh Nguyen, and Sydney Goodwin

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1 Introduction

In modern society, a growing concern has been placed on the detrimental effects of pollution and its costs on the environment and planet as a whole. Consequently, a strong effort has begun to create and explore more sustainable, renewable, and safer alternative energy sources. In recent years, the conversation regarding fuel cells and their applications in modern technology has gained traction as a plausible alternative to more antiquated devices. Originally developed by Thomas Francis Bacon in 1932, and initially used by the United States Navy in submarines during the Second World War, alkaline fuel cells quickly garnered enthusiasm as an alternative energy source. More optimized and safer versions of the fuel cell were developed by another English engineer by the name of Thomas Grub in the 1950's; which led to the technology's application by NASA, who would go on to implement the equipment in their Apollo 11 spacecraft to supply electricity, and to provide the astronauts with drinking water [1]. However, despite early success and excitement surrounding hydrogen fuel cell technology, their full-scale commercialization has yet to come to fruition. Among the forefront of the conversation surrounding fuel cells is questions about their benefits, viability, and overall drawbacks.

1.1 Background

A fuel cell, unlike a storage cell, such as a traditional battery, is an electrical cell that is capable of sustainable replenishment of fuel [2]. Alkaline fuel cells convert hydrogen and oxygen into electricity through a series of chemical redox reactions. The process by which the fuel cell creates electricity begins as hydrogen gas is forced through the anode side of the cell and comes into contact with the catalyst. As it contacts the catalyst, the hydrogen gas (H_2) will be split into two protons and two electrons. The electrons will be conducted through the anode and be used in an external circuit as electrical current, where they will be able to do work. The protons resulting from the splitting of hydrogen gas will be diffused through a proton exchange membrane (PEM) toward the cathode side of the cell. PEM's are semi-permeable membranes which utilize polymers that consist of non-ionic and ionic repeats that are covalently linked with a polymer backbone. Because of the structure of PEM's, they display ionically conductive characteristics while being electrically insulated. This property allows protons to diffuse across the cell, while electrons will be insulated from crossing over towards the cathode. On the cathode side of the cell, oxygen gas (O_2) undergoes a similar reaction, where it is forced into the catalyst and is split into two negatively charged oxygen atoms. The negatively charged oxygen atoms and the positively charged protons combine with the returning electrons to form water, which is released as the fuel cell's exhaust.

As is evident by the process through which the energy is created, the materials used to make up the cathode, anode, catalyst, and electrodes of a fuel cell are important in the overall efficiency of the device. The original alkaline fuel cell developed by Bacon in the 1930's used molten potassium hydroxide (KOH) as an electrolyte. This type of fuel cell utilizes a liquid electrolyte and is unlike many modern fuel cells, which use a solid electrolyte in the form of the PEM. Modern day fuel cells vary in their composition, but the most common alkaline fuel cells are proton-exchange membrane fuel cells, which utilizes the aforementioned proton-conducting polymer membrane and a platinum catalyst to undertake the chemical processes of the cell [3]. Debate surrounding the pros and cons of liquid and solid electrolyte fuel cells still exists today. Liquid electrolyte cells, like those originally developed by Bacon, are attractive as they can operate at sub-freezing temperatures and are among the most efficient types of fuel cells. Conversely, PEM fuel cells face difficulty at sub-freezing temperatures as the membrane must often be hydrated by water. However, PEM fuel cells are less susceptible to corrosion, and offer quicker start up times than their liquid cell counterparts.

Overall, the current climate in modern society suggests a strong push for governments to move away from the current non-renewable energy and seek safer and more efficient alternatives. Undoubtedly, hydrogen fuel cells will be at the precipice of the conversation with regards to such technology. There are numerous benefits to the technology harnessed in hydrogen fuel cells, many of which will be outlined in this paper; these benefits include their overall performance, applications, and safety. In contrast, hydrogen fuel cells are not without their shortcomings – questions about their practicality and large-scale implementation still loom heavily over the future-esc technology and will need to be addressed before we begin to see them in everyday life.

2 Benefit to Society

Hydrogen fuel cells are currently one of the most promising options for alternative energy sources; with capable efficiency and green emissions, they have quickly risen in recent years as a prominent figurehead in the discussion. The primary advantage to hydrogen-based fuel cells is their lack of harmful greenhouse gas emissions. Hydrogen fuel cells are highly optimized as a storage medium as the hydrogen can be stored in the form of a gas or a liquid. In these forms, hydrogen will not deplete until it is fully used up, making it a great source of fuel for emergency generators. Other traditional energy storage sources tend to slowly lose their energy content and require recharging over time [4]. Hydrogen fuel cells have a very high energy conversion rate compared to burning fuels such as gasoline and coal. In general, the energy generated by combustion of coal is only approximately 30% efficient at converting heat energy into electrical power. In contrast, hydrogen as a fuel has demonstrated efficiency as high as 80% in some instances. With less waste and more energy, there is significant conjecture as to whether or not hydrogen fuel cells are less expensive with regards to both costs and their effect on the environment.

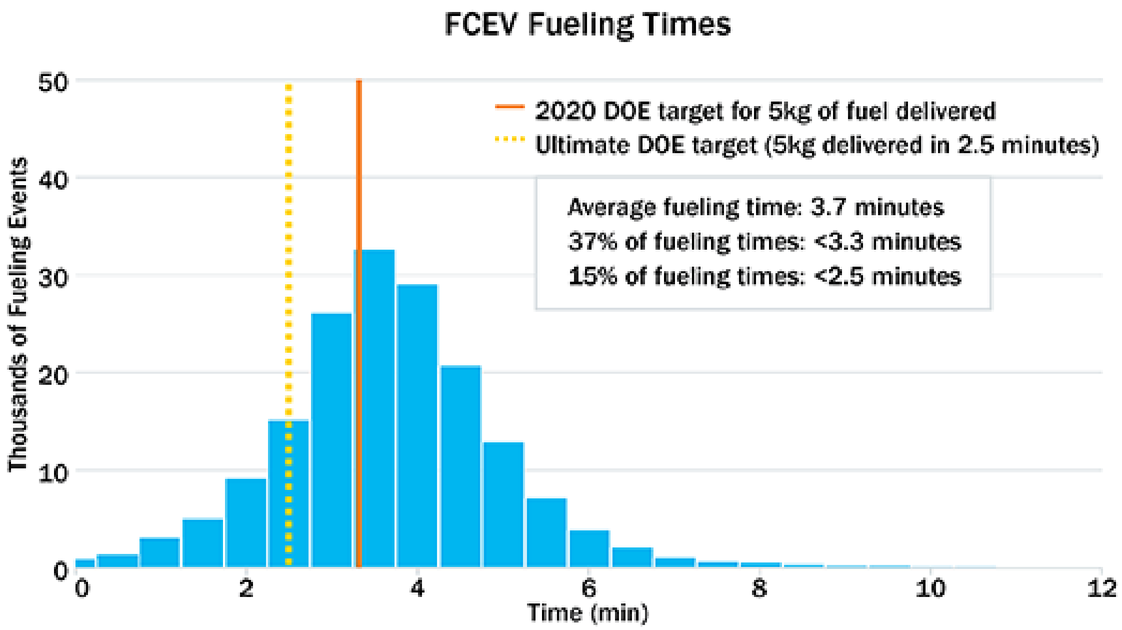
2.1 Environment

In terms of environmental impacts, hydrogen fuel cells are far less negatively impactful on atmospheric air quality when compared to other sources of energy such as fossil fuels. The primary reaction conducted in a hydrogen fuel cell creates three products as a result: electrical current, heat, and water. Because the reaction within the fuel cell does not involve the combustion of hydrocarbon chains, the oxidation of carbon does not take place and greenhouse gases such as CO_2 are not released. Several molecules such as carbon dioxide, nitrous oxide, and methane are capable of climate warming if released into the atmosphere. Molecules that contribute to global warming do so, simplistically, by absorbing the long wave radiation from the sun, which has bounced off the earth's surface, and re-emitting the radiation back towards earth's surface once again. Water vapor, a triatomic molecule with a dipole moment, is in fact a major contributor to the greenhouse warming effect. However, experts suggest that although water vapor is a major player in global warming, the amounts of water vapor in the atmosphere are almost entirely due to natural evaporation, or evaporation accelerated by global warming. This is to say, the emissions of hydrogen fuel cells contribute a near insignificant portion of water vapor into the atmosphere and are undoubtedly less deleterious than other greenhouse gases.

2.2 Consumer application

In application, society can utilize hydrogen fuel cells by powering motorized vehicles such as space rockets and automobiles. There are two common ways to power hydrogen fuel-based vehicles: either by converting the chemical energy of hydrogen into mechanical energy by burning hydrogen in an internal combustion engine, or by reacting hydrogen with oxygen in a fuel cell [4]. There is no combustion process in hydrogen vehicles, as they will almost always use a fuel cell rather than burning the hydrogen. The reaction within the fuel cells uses pure molecular hydrogen as fuel and the electrochemical method of converting the hydrogen's chemical energy to mechanical energy. Large scale implementation of fuel cell powered cars is greatly advantageous to the atmosphere and environment in comparison to traditional combustion engine vehicles. Hydrogen fuel cell powered cars are also very quiet compared to the standard gasoline vehicle and are capable of travelling longer distances. An additional benefit is that their refuel time is remarkably fast in comparison to a gasoline powered car. With a full tank of hydrogen gas, a vehicle can drive nearly 482 kilometres (300 miles) and its tank can be replenished in less than four minutes, as seen in Figure 1 below.

Figure 1: Average time spent fueling a hydrogen vehicle [5].



3 Cost to Society

Despite the clear positives to hydrogen fuel cell technology, the large-scale implementation of the equipment has yet to come to fruition due to several significant drawbacks. The main drawback for fuel-cell electric vehicles (FCEV) is the cost. Since it is a relatively new technology as fuel, the economic advantages do not surmount gasoline. First, there is the initial infrastructure cost. There is almost no infrastructure in place for FCEVs so the capital cost of installing new fuel stations will be high. They would need to be fitted with high-pressure tanks or cryogenic tanks [6]. The former would store the hydrogen in gaseous form, while the latter in liquid form. Gaseous storage is advantageous as hydrogen is pumped into FCEVs in a gaseous form and cooling hydrogen enough to turn it into a liquid uses far more energy [7]. Along with fuel stations, transportation and storage of hydrogen faces the same challenges. Hydrogen fuel storing requires high-pressure or cryogenic tanks. Storage doesn't require the hydrogen to be in gaseous form since it is not being directly pumped yet, so it can be stored in liquid form, and more hydrogen can be stored. However, this would be much more expensive than storing it in gaseous form, which is just at room temperature. The same issue arises for transportation, although transporting in liquid makes more sense because an entire storage facility doesn't need cryogenic tanks, rather just that method of transportation does, whether it be trucks, trains, ships, etc. Since it would be transported in liquid form, more can be transported.

The current average cost of molecular hydrogen is $13.99 per kg, the equivalent of $5.60 per gallon of gasoline. This is extremely expensive compared to the national average gas price of $2.43 per gallon in the USA as of February 11, 2020 [8]. However, hydrogen is much more efficient than gasoline or diesel. A fuel cell paired with an electric motor is two to three times more efficient than a gasoline powered internal combustion engine [5]. The idea that hydrogen is a renewable energy source is what is most appealing to the public and is a major factor in how this source is a "climate-friendly energy chain" [9]. The major desire around hydrogen fuel cells and our society is that it is a product that will lower the carbon footprints of big industries with an end result of creating a greener planet. Hydrogen fuel cells also have better abilities to store electricity when comparing it to the storing abilities of a battery. According to the Ocean Geothermal Energy Foundation, batteries lose approximately 50% of the electricity they start with when put to use, but a hydrogen fuel cell is able to contain the energy and reuse it in a way that is not harmful to the environment. In the end this reusable and economically friendly product has many opportunities to prove itself and eventually be worth its dollar amount.

A paramount issue with regards to hydrogen fuel is the fact that pure hydrogen does not exist in large quantities on earth in a way that we can effectively utilize it. The vast majority (95%) of industrial pure hydrogen is made through steam reforming. Steam reforming is a process that heats methane gas under extremely high temperature and pressure, along with a metal catalyst, in order to partially oxidize the methane gas to carbon monoxide [10]. In the process of this reaction pure hydrogen is able to be obtained. The issue with steam reforming is that the newly formed carbon monoxide gas undergoes a further water-gas shift reaction, where it interacts with the water vapor and becomes fully oxidized into carbon dioxide.

Steam-methane reforming reaction

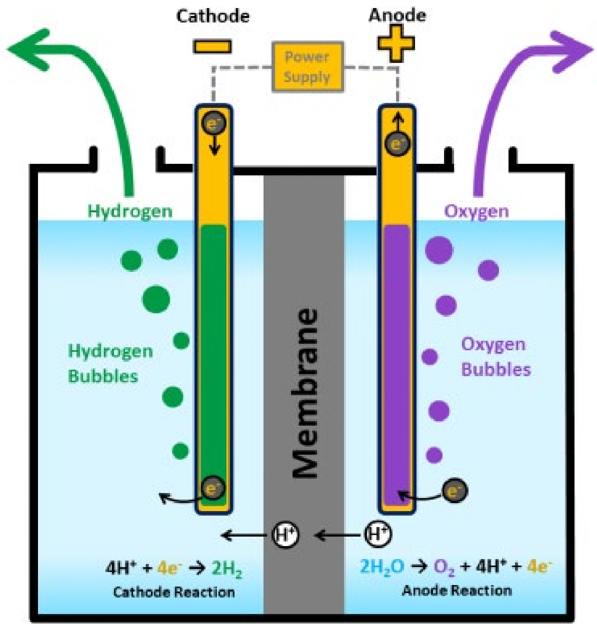
$$CH_4 + H_2O \text{ (+ heat)} \rightarrow CO + 3H_2$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+ heat)}$$

The production of carbon dioxide through this process is a clear detriment to what is supposed to be an otherwise green source of energy. Several other ways to create pure hydrogen exist, but almost all require the use of fossil fuels, and subsequent release of greenhouse gases into the atmosphere. The most promising solution for the hydrogen fuel problem lies with the process of electrolysis. Electrolysis is a reaction where an electrical current is passed through water which allows it to be separated into hydrogen and oxygen. When a current is passed through water, negatively charged oxygen diffuses towards the positively charged anode, and the positively charged hydrogen diffuses towards the negative cathode [11]. There are different methods to perform electrolysis, but the most common method is called polymer-exchange membrane electrolysis (see Figure 2 below). The membrane provides particle transport between anodes and cathodes, allowing extraction of hydrogen from water.

Figure 2: Polymer-exchange membrane electrolysis (PEM)



The primary issue with electrolysis is that it is costly and requires a large input of energy to sustain. In the USA, the majority of energy used in the process of electrolysis still originate from coal-fired power plants [12]. A potential solution is to couple this process to renewable sources of energy such as solar or wind; however, the required infrastructure does not currently exist to implement this strategy on a large scale.

4 Future Outlook

The future of hydrogen fuel cell technology relies on the development of cost-effective manufacturing techniques, improved storage and transportation infrastructure, integrating the technology into the market, and implementing safety codes and standards.

There are a multitude of private agencies around the world attempting to implement and sell hydrogen fuel cell technologies. One such organization has been committed to this goal for the past 60 years. Hydrogenics is a Cummings Inc. company based in Mississauga, Canada with facilities across the globe that design, manufacture, build, and install hydrogen fuel cell technology. They specialize in hydrogen generation, hydrogen fuel cells, and energy storage. They advertise their success from PEM and alkaline hydrogen generators, hydrogen fuel cells for electric vehicles, fuel cell installations for freestanding electrical power plants, critical power and UPS (uninterruptible power supply) systems, as well as innovative methods to store and transport the energy [13]. As previously mentioned, high costs and inefficient storage and transportation methods are current barriers to hydrogen fuel cell technologies. Research and development to reduce the cost and improve the efficiency of the production, storage and transportation of this energy is integral to switching to hydrogen sources. Hydrogenics have developed a “power-to-gas” solution in which the current natural gas infrastructure is used to store and transport energy. Electrolysis generates the necessary power from renewable sources and converts surplus electricity into hydrogen or renewable gas that can be stored and transported in the natural gas pipeline network and underground storage facilities [13]. Benefits of this system include the ability to charge energy for several weeks without needing to discharge it, and a decrease in cost as it relies on pre-existing pipelines and facilities [13].

Safety codes and standards of practice are important areas of development during the implementation of new technologies. The National Renewable Energy Laboratory (NREL) is a federal laboratory within the US Department of Energy that performs research, development, commercialization, and deployment of renewable energy and energy efficiency technologies [14]. Their research on hydrogen fuel cells allowed them to release national templates for hydrogen codes and standards. A publication database was established with links to journal articles, technical reports, conference papers, and presentations regarding hydrogen safety codes and standards. For example, the database contains information regarding hydrogen sensors for purity and leaks as the gas is colourless and odourless [14]. Natural Resources Canada published an executive summary in March 2017 regarding hydrogen fuel cells that includes the Canadian Hydrogen Installation Code (CHIC) as well as other established codes, standards and regulations for hydrogen fueling, storage, and related applications [15]. Hydrogenics lists a multitude of safety certifications from Bureau Veritas, The National Board of Boiler & Pressure Vessel Inspectors, Lloyd’s Register Verification, and The American Society of Mechanical Engineers, to name a few [13]. None of these are associated with the NREL, the US Department of Energy, Natural Resources Canada, or the CHIC [14, 15]. In fact, Bureau Veritas is a private, international Testing, Inspection and Certification (TIC) service [16]. Although mildly outdated, and specific to a particular branch of Bureau Veritas, a scalding report was released by China Labour Watch in 2009 that revealed the company was guilty of extortion, accepting bribes, retaliatory audits and other forms of corruption [16]. Are these private TIC organizations capable of implementing the set of safety codes and standards established by governing bodies? Natural Resources Canada seems to think so; Hydrogenics is listed in their executive summary timeline as the joint venture owner with Endbridge for the first utility-scale power-to-gas plant installation in North America [15]. Both public and private organizations have an impact on the way we produce, distribute and store energy. As hydrogen fuel cells become more affordable and available, both of these sectors need to adapt and work in tandem to ensure the safety of the environment and the public.

5 Conclusion

Hydrogen fuel cells, as they are now, are incapable of mainstream implementation and integration into our society. Despite the immense potential held by this prospective 'green' source of energy, further advancements and breakthroughs in the large-scale production and storage of molecular hydrogen must be attained before any real consideration of a global shift towards using hydrogen fuel cells is made.

For fuel cells to become the environmentally friendly alternative source of energy that they are said to be, we must first be able to produce molecular hydrogen on a grand scale without releasing any greenhouse gasses as a byproduct. Our current best method of doing so is by electrolysis of water, which requires a large amount of energy to allow for the endothermic reaction to occur – effectively storing the energy in the molecular hydrogen. To make this an entirely zero emission process, it is necessary that the energy used for electrolysis is also obtained through energetically 'clean' processes. Following an advancement in the production of usable hydrogen, a major advancement in the storage and transportation of hydrogen fuel is also required. Due to hydrogen's low volumetric density, storing and transporting it is a costly practice of its own. Whether we do so in a gaseous state, requiring pressurized vessels; in a liquid state, requiring temperatures below -252.9 °C; or in a solid state as a hydride, our current methods of doing so greatly add to the cost of readily available hydrogen fuel.

Having retouched on the two largest problems faced by the hydrogen fuel cell industry, we ask the question: is this a worthwhile pursuit? A successful integration of hydrogen-based power could be an answer for a greener global energy source, but there is still a large amount of research and innovation required before that goal can realistically come into sight. Many could argue that a combination of solar power and batteries are closer to realizing the goal of a greener global energy source given enough funding for further research and innovation. Considering where the current innovation on hydrogen fuel cells stands, it is hard to see it as a realistic solution to the current international goal of reducing global greenhouse gas emissions in the required timeframe. As such, although hydrogen fuel cells prove themselves to be a prospective lead into the future of large-scale energy production, it does not currently have the means to be justified as a short-term pursuit as a clean energy alternative.

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