THE APPLICATION OF PROTON EXCHANGE MEMBRANE FUEL CELLS IN PASSENGER VEHICLES FOR A SUSTAINABLE FUTURE

Luke Rattay, lar138@pitt.edu, Mena, 10:00, Joshua Young, jdy15@pitt.edu, Mandala, 2:00

Abstract—*Proton exchange membrane fuel cells (PEMFCs) are types of electrochemical cells that convert hydrogen and oxygen gases into electrical energy. This paper presents a brief historical background into the creation of PEMFCs and describes their fundamental operations. The electrochemical processes behind PEMFCs, such as the oxidation-reduction reaction that fuels them, are also covered. Following this is a description of the control systems that optimize PEMFC operation in vehicles. A discussion of the Toyota Mirai provides detail and clarity of the application of PEMFCs in passenger vehicles and the current market for these vehicles. The Mirai's lack of carbon emissions and larger range over plug-in electric vehicles make it a potential competitor in current and future markets as a more sustainable vehicle.*

Following the discussion of the Mirai is a comprehensive analysis of the potential dangers of platinum depletion due to mass PEMFC vehicle production and the measures that must be taken to overcome this depletion. Overcoming platinum depletion is integral to making hydrogen power sustainable and reliable for the future. Readers will discover the viability of PEMFC vehicles as well as the challenges that still face them in becoming a widespread technology. Overall, fuel cell vehicles have the potential to become a more sustainable alternative to other types of vehicles, but more research and dedication to material conservation must be observed to propel them into markets of the near future. Readers should also understand that a greater community awareness and acceptance of PEMFC vehicles is required to catalyze their integration into modern society via increased demand and the construction of new fueling stations.

Key Words—Alternative fuels, Clean energy, Electrochemistry, Fuel cell vehicles, Hydrogen energy, Proton exchange membrane fuel cells (PEMFCs), Sustainability, Toyota Mirai

FUEL CELLS: PROPULSION TO A SUSTAINABLE FUTURE

The world is filled with vehicles, most of which run on internal combustion engines. The massive amounts of carbon dioxide that pour into the environment due to these vehicles are slowly creating irreversible climate change. According to the International Energy Agency, the burning of fossil fuels comprised 67% of the world's energy consumption in 2015 but accounted for 99.4% of the world's CO_2 emissions [1]. The burning of fossil fuels in internal combustion engine vehicles (ICEVs) will continue to negatively impact the environment unless other means of powering vehicles take over the automobile market.

To prepare the world for future societies, it is necessary to have sustainable alternatives to the ICEVs that are polluting the atmosphere and depleting the world's fossil fuel resources. According to the United States Environmental Protection Agency, sustainability is the principle that society should "…create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations" [2]. To implement a sustainable environment, the current generation must preserve natural resources for generations to come, and this preservation starts with the reduction of carbon emissions. Battery electric vehicles (BEVs), the most common alternative to ICEVs, have been unable to compete due to lengthy recharging times and a lack of sufficient mileage per charge. To make sustainability a legitimate possibility, a more adequate alternative must join the automobile market. The hydrogen fuel cell vehicle (FCV) can be a more sustainable, efficient alternative.

The FCV improves upon the areas where BEVs are lacking while still offering a cleaner, more sustainable alternative to ICEVs. FCVs are powered by PEMFCs, a specific type of fuel cell in which protons pass through a semi-permeable membrane while electrons travel through an external circuit [3]. The PEMFC's function is moderated by several control systems that maintain its delicate reaction conditions while supplying sufficient amounts of power to the FCV. These control systems are paramount to the operation of vehicles like the Toyota Mirai, one of the first FCVs launched in the United States. As with any technology, there are some ethical concerns involved with PEMFCs, namely the overuse of platinum in their production and the carbon emissions associated with that production. Limiting platinum use is a key factor in maintaining the sustainability of this technology, and measures are currently being taken to correct these manufacturing concerns. The PEMFC is a technology that could transform the future of sustainable transportation.

THE BASICS OF PEMFCS

A Brief History of PEMFCs

The PEMFC originated as an idea in the late 1800s. In the journal *Renewable and Sustainable Energy Reviews*, Omar Sharaf et al. describe the early history of PEMFC development [3]. Chemist Sir William Grove used his electrolysis background to create a process that could generate electricity by combining hydrogen and oxygen. In 1959, Francis Thomas Bacon brought Grove's dream to reality by demonstrating the first fully-operational fuel cell. NASA adopted the use of PEMFCs and alkaline fuel cells during the Gemini and Apollo missions of the 1960s [3]. As time went on, more variations of fuel cells were created, with PEMFCs rising as the most common form used for modern applications. PEMFCs also gained reliability and durability over the other types of fuel cells, which allows for their growing use in the public and private sectors, especially transportation [3].

PEMFCs in Comparison with Other Power Sources

One of the main reasons that PEMFCs are growing in popularity in the transportation industry is that they present a more clean, sustainable, and efficient way to produce energy, far superior to that of common ICEVs. Since hydrogen is one of the most abundant elements on the planet, using it to power vehicles is less resource-depleting than burning fossil fuels. Therefore, hydrogen is a more sustainable fuel source than fossil fuels.

Simply, PEMFCs convert hydrogen and oxygen gases into water, heat, and electricity via a thin membrane that allows protons to pass through while electrons are routed through an external circuit, which provides power to whatever source is using the cell. At the anode, the hydrogen splits into protons and electrons, which travel by separate routes to the cathode, where the protons and electrons unite with oxygen to form water. The process by which this reaction occurs is close to that of a battery [3].

While PEMFCs are fairly similar to batteries, there are a few key differences. Unlike batteries that need to be charged, PEMFCs can operate for as long as fuel is provided, and products of the reaction are regularly removed. As Sharaf and his colleagues explain, the energy in batteries is stored mainly in its electrodes, the metal conductors at either end that interact to let electricity flow between them [3]. PEMFCs also have electrodes, but rather than storing the energy produced, they are merely a means of converting energy from one form to another. Because the battery's electrodes store the energy, there comes a point where all the potential energy from those electrodes has been converted, and the battery is no longer useful. The battery then must be either recharged or disposed of. In PEMFCs, the reactants are supplied separately and thus the components of the cell are not used up while it operates. In this way, as long as reactants are supplied and products are removed, the cell can continue to produce electricity indefinitely [3].

PEMFCs implement a more direct energy conversion than combustion engines. As Sharaf et al. write, "…fuel cells produce electrical work directly from chemical energy. While in the case of heat engines, producing electricity is a multi-step process that involves combustion to produce thermal energy from the internal chemical energy of the fuel. Then this thermal energy is converted into mechanical energy, and finally this mechanical energy is converted into electrical energy through the use of a generator" [3]. The authors describe how the efficiency of a one-step process, like PEMFC energy conversion, is almost always greater than that of a multi-step process, like combustion engine conversion [3]. Each step in the conversion of energy inevitably results in a loss of energy to the surroundings in unwanted forms, such as heat or sound. In PEMFCs, there is only one step in the energy conversion process, so there is less net energy loss than in combustion engines, where the three-step process of energy production leads to more heat, sound, and other unwanted byproducts [3]. As a result, the greater efficiency of the PEMFC makes it more sustainable than the ICEV by wasting fewer resources during energy production.

THE SCIENCE BEHIND THE CELLS

Electrochemical Processes

To begin discussion of the PEMFC's functionality, one must first understand the inner workings of the cell. At the input terminal of the PEMFC, hydrogen fuel is supplied. It combines with oxygen gas from the atmosphere to power the cell in correspondence with the reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + W_{ele} + Q_{heat} \qquad [3]$$

This equation is the overall chemical equation for the reaction that occurs in PEMFCs. Hydrogen and oxygen react to produce water, heat energy (Q_{heat}), and electrical work (W_{ele}). The equation can also be broken down into individual net-ionic equations that occur at the different electrodes [3]. As described in the textbook *Fuel Cell Fundamentals*, the net-ionic equation for the anode is:

$$H_2 \rightarrow 2H^+ + 2e^- \qquad [4]$$

Once hydrogen gas enters the cell, it is oxidized due to oxygen's larger reduction potential. Oxygen is more electronegative, and it effectively "steals" the electrons from the less electronegative hydrogen. The hydrogen molecules gather on the metal surface of the anode, where the electrons travel through the metal electrode to the external circuit and the protons travel through the electrolyte membrane toward the cathode. The dissociation of the hydrogen into protons (H^+) and electrons (e^-) is visualized in Figure 1 [4].

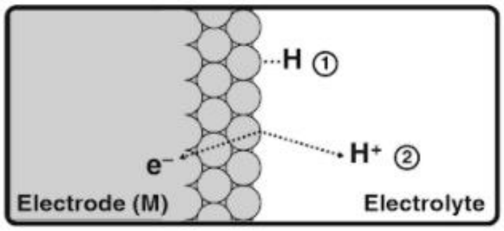

FIGURE 1 [4]
Hydrogen dissociation at the anode

The “H” in the figure represents a hydrogen molecule. As seen in Figure 1, the molecule contacts the metal surface of the anode, and the electrons (e^-) and protons (H^+) part ways. After the subatomic particles travel through their respective sub circuits of the PEMFC, they join oxygen at the cathode and fulfill the following reduction half-reaction:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad [4]$$

According to the authors of the textbook *Sliding-Mode Control of PEM Fuel Cells*, “In the cathode’s surface the oxygen molecules react with electrons from the external circuit and protons from the membrane to produce water. In the process, the only by-product is water, in vapor and liquid phases” [5]. In a similar fashion to the way that the metal anode provided a surface for hydrogen atoms to dissociate at the beginning of the reaction, the metal cathode provides a surface where the protons and electrons can rejoin to form water at the reaction’s culmination [5]. Additionally, the fact that water is the only byproduct of the reaction is another reason to praise the sustainability of a PEMFC. The lack of harmful emissions preserves the atmosphere for the benefit of future generations. Figure 2 provides a more detailed display of the PEMFC.

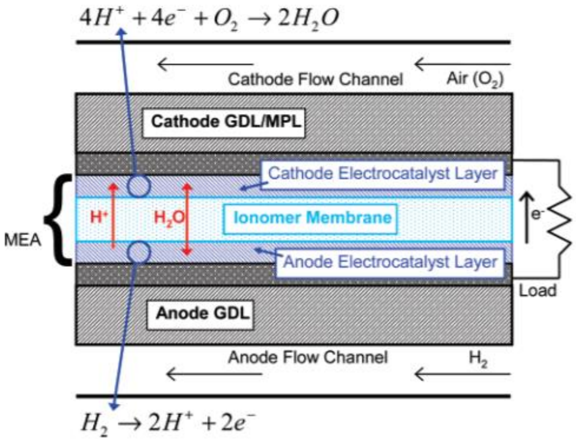

FIGURE 2 [6]
Visual representation of a PEMFC

The metal anode is pictured at the bottom of Figure 2, and the cathode appears at the top. Notice the red arrow depicting proton (H^+) travel through the colored membrane electrode assembly (MEA). Meanwhile, the electrons (e^-) can be thought of as bypassing the membrane in the wire to the right side of the figure. The flow of air, containing O_2, provides the oxygen necessary for the cathode half-reaction. One may notice that the cathode half-reaction is different in this figure than the equation mentioned earlier in this section. Both equations convey the same process; they simply use different stoichiometric coefficients. Although it may seem that this reaction can occur indefinitely, many external, computerized systems are required to manage it and ensure optimal performance [6].

PEMFC Control Systems

PEMFCs require several control systems to keep the reaction rate as high as possible. According to W.R.W. Daud, et al., writers for the journal *Renewable Energy*, these systems are responsible for the addition of reactants, removal of products, temperature management, moisture control, and energy flow [7]. Without the proper external system controls, the PEMFC is incapable of operating for extended periods of time and will eventually malfunction [7]. Figure 3 shows a basic representation of the various control systems oriented outside of the PEMFC.

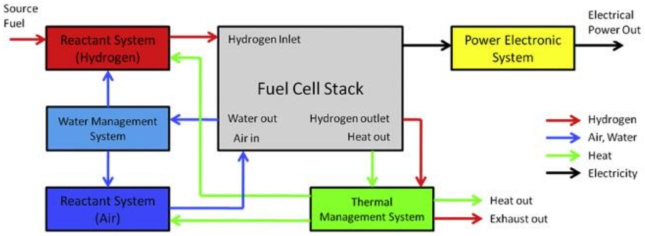

FIGURE 3 [7]
Layout of the PEMFC control systems

As shown in Figure 3, there is an array of subsystems that exist outside of the PEMFC to ensure efficient operation. This efficiency maintains the sustainability of the fuel cell by reducing the amount of wasted resources and maximizing energy output. These systems use various sensors to manage the PEMFC and alter the reaction conditions for optimal performance. Shown by the image, these subsystems include the reactant, thermal management, water management and power electronic systems [7].

The reactant subsystem is responsible for supplying the correct stoichiometric ratios of reactants based on the load experienced by the PEMFC. This system uses a fuel processor to supply the gaseous hydrogen to the anode, where oxidation occurs. To maintain proper hydrogen pressure at the anode, a backpressure regulator is utilized. Oxygen is stored in a compressed air tank and supplied to the cathode by a blower.

Daud et al. note that although supplying hydrogen at a high pressure increases the rate of the reaction, powering the fuel processor steals usable electricity from the vehicle [7]. Wasting electricity to over pressurize hydrogen is pointless because the reactant subsystem is designed to ensure that maximum electrical power is provided to the vehicle from the cell. The system also maintains the delicate balance of hydrogen and oxygen in the PEMFC and keeps the reaction from halting. While managing the input of reactants is crucial to optimal PEMFC performance, the removal of products, especially heat, is equally important [7].

Nearly half the energy produced by a PEMFC is in the form of heat, which must be removed to maintain the optimal reaction temperature. Although higher temperatures can improve reaction rate, the thermal management subsystem is necessary to ensure the longevity and continued efficiency of the fuel cell. Excessive heat, produced by the oxidation-reduction reaction, can dehydrate the electrolyte membrane, reducing its proton conductivity [7].

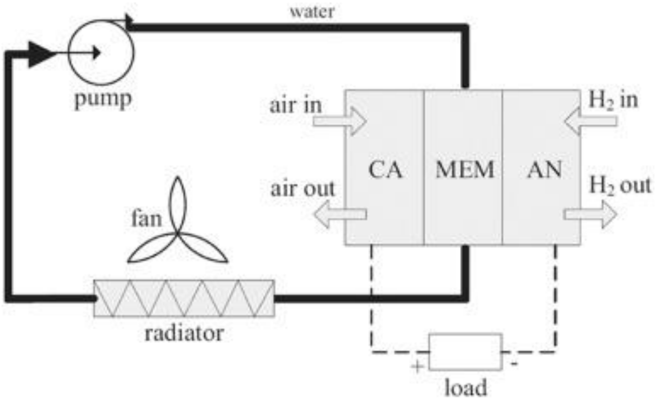

FIGURE 4 [7]
Layout of the thermal management subsystem

As displayed by Figure 4, the thermal management subsystem ensures optimal PEMFC temperature by providing a constant supply of cool water. After being pumped into the electrolyte membrane, the warm water exits the PEMFC and enters a fan cooled radiator system. The now cooled water exits the radiator and is then recirculated through the PEMFC by a pump. As Daud et al. claim, the optimal reaction temperature for a low-temperature PEMFC is between 65 ℃ (149 ℉) and 85 ℃ (185 ℉), so this type of system is necessary for proper function. The addition of a small amount of water may be essential to keep the PEMFC cool, but it is also produced in excess by the reaction and therefore must be removed [7].

Since water is the only physical product of the PEMFC reaction, it must be continually removed so that smooth operation can be achieved. At a low temperature, such as that required by PEMFCs, the amount of water produced by the reaction can cause flooding and adversely affect performance. When water invades the porous membrane, hydrogen gas and oxygen conductivity are greatly reduced. Although excess water in the PEMFC can lead to poor operation, Daud et al. mention that the electrolyte membrane must also be kept moist to prevent dehydration [7]. Figure 5 shows the basic layout of the water management subsystem around the PEMFC.

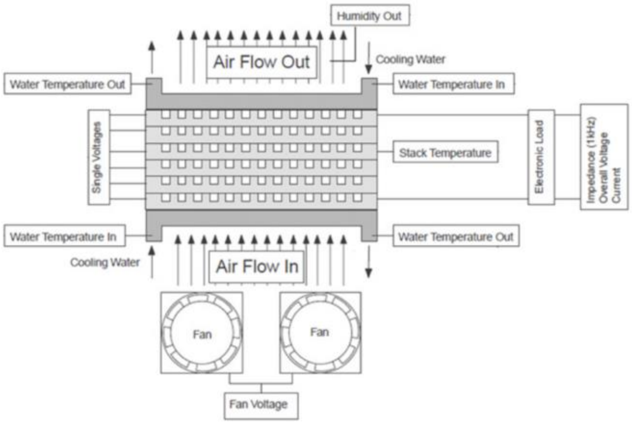

FIGURE 5 [7]
Layout of the water management subsystem

As seen in Figure 5, the water management subsystem consists of an internal and external humidification system, and both maintain proper moisture levels within the PEMFC. A system of fans is utilized to keep a constant flow of moist air blowing through the PEMFC. The external humidification system controls the humidity of the reactants to maintain optimal reaction conditions. The internal humidification system keeps the electrolyte membrane hydrated by injecting water directly into the PEMFC. To maintain the humidity levels within the PEMFC, relative humidity sensors are used to control the addition and removal of moisture within the PEMFC. [7].

While managing the reaction itself is crucial to optimal PEMFC performance, a system that manages the electrical power, the most important of the products of reaction, is needed to ensure that the vehicle can run efficiently and reliably. The power management system, uses electronic devices to deliver the electricity produced by the PEMFC to the car. Daud et al. note that while driving, a car requires varying amounts of power based on the degree of acceleration input by the driver [7]. Therefore, they argue that the voltage and current demanded by the electric motor will vary based on the acceleration required.

Since the direct current (DC) power produced by PEMFCs can be unstable, the power management subsystem is responsible for delivering the required voltage and current on demand and without delay. The typical PEMFC can produce between 25 and 50 volts depending on the electrical load demanded by the vehicle, and the power management system controls the voltage delivered to the engine. This is accomplished by using an external circuit which contains voltage regulators, DC/DC converters and chopper circuits. Some components of a vehicle require alternating current (AC) to run properly, so the power management subsystem also contains a DC/AC converter. While ensuring that the PEMFC can provide the proper voltage under high demand is necessary for efficient driving, a system is needed to guarantee that the PEMFC is never depleted of reactants under such an extreme load [7].

A prevalent issue encountered when using PEMFCs to power vehicles is that the reactants can be depleted quicker than they are supplied by the reactant subsystem, especially under an extreme load. This phenomenon, called fuel starvation, usually occurs during periods of extreme vehicle acceleration and can permanently damage the fuel cell. The main effect of fuel starvation is reduced voltage, which can lead to vehicle power loss and potentially dangerous driving situations. Starvation can also cause previously reacted hydrogen ions to produce hydrogen gas at the cathode and oxygen ions to produce oxygen gas at the anode. These unwanted gases can burn holes in the catalyst layers if they interact with the incorrect catalyst. This occurs because the catalysts are specially formulated for the proper reactants. To combat the issue of fuel starvation, this subsystem supplies excess oxygen and hydrogen gases to the PEMFC when it is under excessive load. This additional supply of reactants does increase power production, but the process of supplying the reactants also consumes power. As a result, many computerized control methods are in place to ensure that the optimal amount of power is produced by the PEMFC [7].

PEMFC Components

While the process controls that manage PEMFCs are tremendously important to efficient power production, the physical components of PEMFCs also contribute to their performance. According to an article written by Sara Evangelisti et al. for the *Journal of Cleaner Production*, one of the most important components of a PEMFC is the electrolyte membrane [8]. This membrane is specially designed to only allow the hydrogen cations to pass through, forcing the electrons to travel through an external circuit. Thus, the electrolyte membrane is partially responsible for providing the electrical current that supplies the vehicle with power.

The most commonly used membrane material for commercial PEMFCs is perfluorosulfonic acid (PFSA). The most common PFSA membrane used in PEMFCs is called Nafion, produced by DuPont [8]. According to Evangelisti et al., “PFSA membranes are relatively strong, have high proton conductivity and are stable in the chemical environment of the fuel cell” [8]. Therefore, PFSA membranes are the best option to achieve optimal fuel cell efficiency and sustainability. By not allowing electrons to pass through, PFSA membranes ensure that all available energy is utilized in the reaction. The electrolyte membrane is the innermost component of a PEMFC, surrounded by the gas diffusion layer (GDL) [8].

The GDL is crucial for providing the platinum catalyst layer with an even supply of hydrogen and oxygen gases to ensure the most efficient reaction. The GDL is usually made of woven carbon cloth or carbon paper which is coated with polytetrafluoroethylene (PTFE), a hydrophobic compound, to keep water from clogging it [8]. To create an intermediary between the GDL and the platinum catalyst layer, a micro-porous layer (MPL), made of graphite coated with PTFE, is placed in between. The platinum catalyst layer, usually made into an ink, is printed onto a carbon black support structure. The membrane is placed between the layers of catalyst, GDL and MPL and hot pressed together to form the MEA as shown in Figure 6 [8].

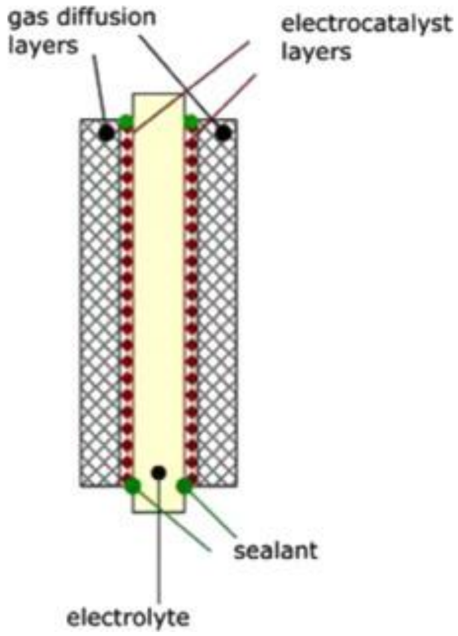

FIGURE 6 [3]
Membrane electrode assembly

The MEA, as depicted in Figure 6, is sandwiched between the bipolar plates to make the most basic PEMFC unit. The bipolar plates, comprised of the anode and cathode, play a major role within the PEMFC. The bipolar plates provide the reactants within the cell, manage water, disperse heat, and carry electricity [8]. The bipolar plates are commonly made from stainless steel, making them one of the largest weight contributors to PEMFCs. A silicone gasket is used to seal the bipolar plates to the MEA [8]. Figure 7 shows the basic arrangement of a single PEMFC cell.

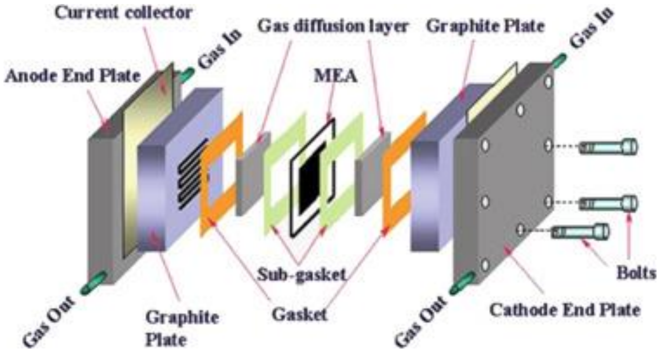

FIGURE 7 [3]
Exploded view of a PEMFC

Figure 7 provides a look inside a PEMFC, showing the arrangement of the various layers and gaskets between the bipolar plates. However, a PEMFC as depicted does not produce nearly enough power to run a vehicle. To provide the voltage required by a vehicle, multiple PEMFCs are clamped together between two end plates to form a fuel cell stack, around which the control systems are oriented. The fuel cell stacks utilized by vehicles contain hundreds of individual cells [8].

THE TOYOTA MIRAI: A MODERN PEMFC APPLICATION

FIGURE 8 [9]
The Toyota Mirai

One current application of the PEMFC is found in the Toyota Mirai (shown in Figure 8), a fuel cell vehicle that is attempting to kickstart the use of hydrogen power in the United States [9]. The Mirai is a major step forward in the promotion of sustainable vehicles in the United States, as it presents the first mass-produced and emissions-free alternative to ICEVs that does not require long charging times and battery power. The fuel cell stack inside the Mirai is supplied with hydrogen via a pressurized fuel tank and utilizes oxygen from the surrounding air [10]. The energy produced in the fuel cell stack then powers an electric motor, via a power control unit. The fuel cell stack has a power output of 3.1 kilowatts per liter of hydrogen, which was the world's best power output in 2014 [10]. Refueling time takes only three minutes, immensely faster than the 7-8 hours required to fully recharge electric vehicles. The vehicle can reach 300 miles on one tank and can start in temperatures as cold as -22°F (-30°C) [10]. Toyota certainly has high hopes for the Mirai and has implemented the PEMFC into a vehicle quite well.

A major improvement for the Mirai over previous fuel cell vehicles is the quality of the fuel cell stack. As mentioned in Toyota's video, "Fuel Cell Stack," the PEMFC stack in the 2016 Mirai was just about half the size of a 2008 fuel cell stack in both volume and weight, thanks to new technology allowing for more compact cells in the stack [11]. The new stack is compact enough to fit below the floor of the vehicle, which can provide a lower center of gravity for the car and enhance cornering ability. The stack is composed of 370 individual cells, which each have a "thinner electrolyte membrane, bringing improved proton conductivity" [11]. The video goes on to mention that "the diffusion layer is also thinner and less dense, leading to enhanced diffusion" [11]. These new developments improve electrode reactions significantly, allowing for more electricity to be generated by more compact cells. The video also mentions new 3D fine-mesh flow fields (pictured in Figure 9), which provide an even supply of air to and prevent the buildup of water in the cells. This is important for maintaining optimal cell performance [11]. New technology has allowed for improvements on previous fuel cell vehicles, and the Mirai's fuel cell stack is a fantastic example of these improvements, which promote the sustainability of the car by making it more fuel efficient.

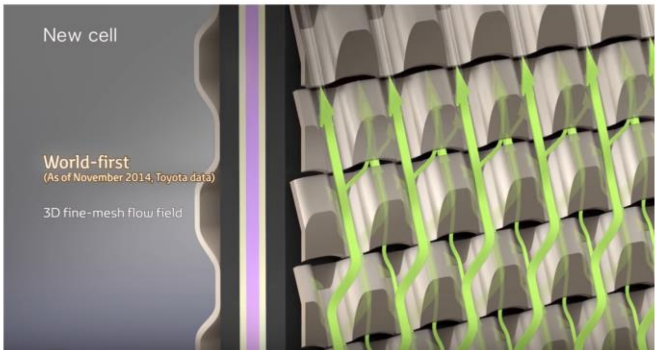

FIGURE 9 [11]
3D fine-mesh flow field

In another Toyota video, titled "How Fuel Cell Vehicles Work," the company expressed its intention to share the technology with others by sharing its intellectual property, including over 5000 patents. As Craig Scott, a national manager of Toyota's advanced technologies group mentioned, "A big part of [the sharing of our intellectual property] is about sharing what we've learned over the last 22 years of developing this technology, but also finding a way to come together and build new things" [12]. The unprecedented sharing of Toyota's patents could jump start the development of more hydrogen-powered vehicles and a more sustainable vehicle market for the future.

The Challenges of New Automobile Technology

The release of Toyota's intellectual property could prove to be beneficial to both the fuel cell vehicle industry and Toyota itself. As author Melissa Riofrio mentioned in her article for the automobile company, "The first Toyota Mirai to be sold in the United States might as well be the first car on Mars. It lands on a planet that can't easily support hydrogen fuel-cell vehicles. It's kept alive only by elaborate and expensive means" [9]. This is certainly the case, as there was only one hydrogen fueling station in Northern California at the time the first Mirai was sold there. In years since, more Californian stations have been built, but driving the Mirai is still very limited by the location of fueling stations. With a range of 300 miles per tank, the Mirai cannot travel more than 150 miles away from a station unless there are two within its driving range. This range limitation is a burden to anyone purchasing a Mirai, as is the $70 expense to fill the tank and the roughly $58,000 cost to buy the car [9]. Because vehicles must be affordable to be a sustainable option for consumers, some incentives are necessary to promote sales of the Mirai. To encourage sales, Toyota has offered to pay for three years worth of fuel (up to $15,000) for anyone purchasing a Mirai [9]. Even with three years of free fuel, the Mirai is going to need more assistance from companies willing to build hydrogen stations and consumers willing to take a risk on new technology. Hopefully with time, the air-polluting ICEVs that cruise the streets today will be a thing of the past, replaced with sustainable vehicles like the Mirai, that are so emissions-free they can be started inside the car dealership [9].

POTENTIAL ETHICAL AND ENVIRONMENTAL RISKS

Are PEMFCs Really Greener than the Competition?

PEMFC vehicles, such as the Toyota Mirai, have been introduced to the world markets as a more sustainable replacement to ICEVs and BEVs. The most advertised environmental advantage of PEMFC vehicles over the competition is that their only emission is water vapor. However, it is necessary to look further than the use phase of a vehicle to determine its total environmental effect. As Evangelisti et al. proved in their article for the *Journal of Cleaner Production*, the carbon emissions produced during a vehicle's manufacturing are responsible for a large portion of total emissions over its life [8]. These authors performed a comprehensive life cycle assessment (LCA) of PEMFC vehicles, analyzing their use, manufacturing, and end-of-life phases in comparison to ICEVs and BEVs. The LCA method calculates the total emissions and energy use over the complete span the PEMFC's existence, as shown in the flow chart in Figure 10 [8].

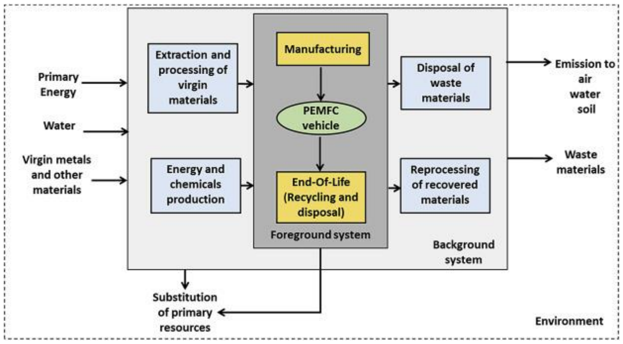

FIGURE 10 [8]
Flow chart depicting the focus of the LCA

As visually depicted by Figure 10, the LCA accounts for everything from raw materials used to produce a PEMFC vehicle to the effects of waste disposal at the end-of-life stage. The study shows that during the use phase, PEMFC vehicles are far superior when compared to ICEVs and BEVs [8]. There is also a negligible difference between the three vehicle types when it comes to the environmental effect of end-of-life disposal. However, the manufacturing phase is where PEMFC vehicles suffer a huge setback when considering global warming potential (GWP). Evangelisti et al. stated, "…the total GWP impact of a FCV is about 16-ton CO_2 [equivalent] compared to ∼8-ton CO_2 [equivalent] for a ICEV" [8]. Figure 11 shows a graphical comparison of the GWP during the use, disposal and manufacturing of BEVs, ICEVs and FCVs.

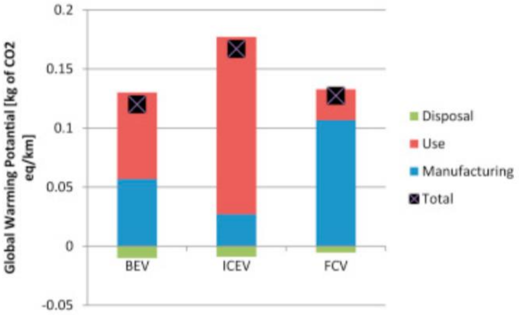

FIGURE 11 [8]
Graph of the GWP of BEVs, ICEVs and FCVs

As shown by Figure 11 the GWP of the use phase of PEMFC vehicles is much lower compared to the others, while the manufacturing phase poses a much greater environmental risk. This environmental risk also poses a major threat to the sustainability of the PEMFC since the manufacturing phase requires a significant volume of natural resources and causes a fair amount of pollution. The components that cause the bulk of the GWP for the manufacturing of PEMFC vehicles are the catalyst layer, GDL and hydrogen storage tanks. The platinum catalyst puts a great strain on the world platinum supply, for Evangelisti et al. state that the autocatalyst market accounts for "…more than 40% of the total demand…" for platinum [8]. Both the GDL and hydrogen fuel storage tanks are made of carbon fiber, which requires a great amount energy to produce. Creating carbon fiber involves heating polyacrylonitrile fibers, the main polymer component of carbon fiber, to upwards of 3092°F (1700°C) [8]. Hence, the production of carbon fiber requires a great input of energy and emits a staggering volume of carbon dioxide at nearly 20 tons of CO_2 per ton of carbon fiber produced [8]. In all, PEMFC vehicles show the potential of being a sustainable alternative to ICEVs and BEVs, but substantial improvement is needed in the manufacturing phase, such as carbon fiber and platinum reduction.

Combating Platinum Depletion

As mentioned previously, PEMFC vehicles boast zero emissions during operation, but some concerns have arisen surrounding the manufacturing of PEMFCs and the environmental hazards that come from implementing platinum in their MEAs. This potential for environmental hazards brings into question the sustainability of PEMFCs because of the pollution and resource depletion caused by the manufacturing stage. According to a study conducted by Lucien Duclos et al. for the *Journal of Cleaner Production*, a lot of this environmental stress can by removed by recycling platinum [13]. The most efficient process currently available can recover 76% of platinum from PEMFCs, but the authors of this study note that the world platinum market only recycled 17% of its platinum in 2012 [13]. The lack of platinum recycling is having a negative impact on the environment and making PEMFC production costlier and less sustainable. Duclos et al. mention that 30-40% of fuel cell manufacturing costs come from platinum extraction, which presents a big target area for cost improvement by either reducing the amount of platinum used by PEMFCs or using more recycled platinum rather than using only primary platinum (i.e. "new," unrecycled platinum) [13]. Reduction of platinum consumption by PEMFC manufacturers could also reduce environmental impact in addition to reducing costs.

While studies continue to be done to reduce the amount of platinum required in PEMFC production, recycling platinum is a technology that is currently available and could improve the environmental impact tremendously, causing PEMFC manufacturing to become a more sustainable process. Some platinum recovery methods mentioned in this study include pyrometallurgy (metal melting), hydrometallurgy (metal dissolution), and substrate removal by dissolution or incineration. Each of the three processes involves five steps: leaching, extraction, regeneration, precipitation, and filtration of the final product. For this particular study, the first two steps were altered using different combinations of variables, and the results found that hydrogen peroxide (H_2O_2) solvents had the best overall performance. These solvents recovered 76% of the platinum when tested, which indicates that the PEMFC industry is far more capable of recycling platinum than the 17% of used platinum that was recycled in 2012 [13].

After determining the extent of recyclable platinum waste, the authors of this study sought to determine how much impact a change in platinum recycling habits would have on the environment. The results were astoundingly clear: platinum recycling drastically reduces the environmental impact of PEMFC production. Figure 12 displays the environmental impact from the production of PEMFCs without recycled platinum [13].

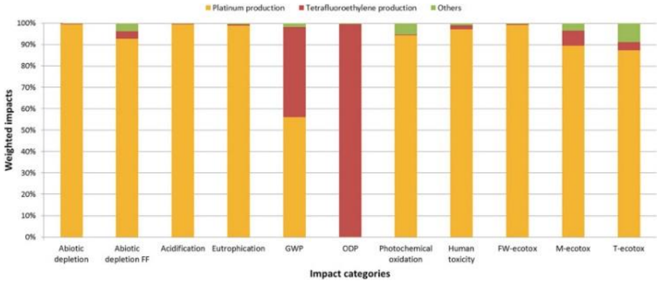

FIGURE 12 [13]
Environmental impact of regular PEMFC production

With exception to GWP and ozone depletion potential (ODP), almost every category of negative environmental impact is dominated by platinum production, indicated by the yellow portion of the bars, meaning that the vast majority of damage done to the environment by the production of PEMFCs is due to the platinum that they require. After testing the environmental impacts of PEMFCs without recycled platinum, they tested the impacts of PEMFCs with recycled platinum and compared results from the two tests [13]. The comparison of methods can be found in Figure 13, where the lighter portion indicates post-recycling effects.

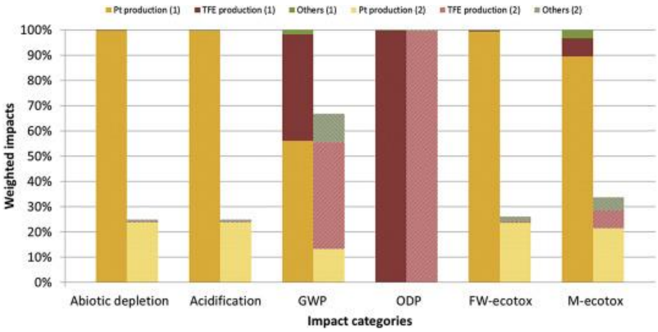

FIGURE 13 [13]
Compared impacts of regular and recycled-platinum PEMFC production

In some areas, such as abiotic depletion and acidification, the recycling of platinum decreased environmental impact by as much as 75%, enough to make PEMFCs a viably sustainable alternative to traditional means of energy production. The authors of this study came to a similar conclusion, stating, "…the assessment reveals that the MEA life-cycle impact can be reduced by 60% if electrode recycling is carried out at the end-of-life stage of the fuel cell by the H_2O_2/Solvent recycling process. In addition, the main impact category decrease is proportional to the platinum recycling rate" [13].

Essentially, by using the most optimal form of platinum recycling, the overall negative impact of PEMFC production on the environment can be reduced by 60%. Additionally, any increase in platinum recycling will correlate proportionally to a decrease in environmental impact. With this knowledge, it seems only appropriate to immediately implement the H_2O_2/Solvent process mentioned by these researchers in any PEMFC production facility worldwide [13].

While manufacturing companies ultimately have the choice whether to use recycled platinum or not, it makes the most ethical sense to reduce environmental impact and improve sustainability as much as possible, especially in an age where environmental issues appear almost constantly in headlines. The more sustainable a technology is, the more the general public will be willing to buy it, and the less damage will be done to future generations. It also makes economic sense for companies to invest in recycled platinum because it will allow for them to produce PEMFCs and vehicles, such as the Toyota Mirai, at lower prices. It is possible that current firms view platinum recycling as a risky investment and shy away from spending money on recycling platinum. However, investing in platinum recycling will lower vehicle prices in the long run, and as more vehicles are purchased at the same profit margins, companies will make more money, allowing them to become financially sustainable. This price drop will incentivize the purchase of FCVs and grow the PEMFC industry, moving society toward a cleaner environment.

PEMFCS: THE POTENTIAL TO MAKE A FUTURE IMPACT

The world is moving toward more sustainable technology to protect resources for future generations, but a major hurdle in this push for sustainability is the fossil fuel burning vehicles that dominate the current infrastructure. PEMFC vehicles provide a means to clear that hurdle, offering a superior alternative to BEVs and holding the potential to be eco-friendlier than any vehicle that the world has seen before. As world manufacturers shift into a cleaner, more environmentally-friendly way of production, PEMFC vehicles have the potential to replace ICEVs. The fossil fuels that have become a norm in modern society may one day be replaced by cleaner, more sustainable energy forms. PEMFC technology is nearly at the point of competition with that of fossil fuel vehicles, and a joint investment by the community and manufacturers to improve hydrogen fueling infrastructure and reduce platinum overuse could bring FCVs into contention with current markets. Another potential method to encourage hydrogen-powered vehicles would be to subsidize hydrogen fuel or further tax gasoline to make refueling prices competitive.

The Mirai is the first step in a long process to establish a new hierarchy of sustainable, clean energy vehicles. Assuming that automakers take advantage of the research that Toyota released and world governments cooperate, there could soon be competition in the FCV market, leading to further development and refining of PEMFC technologies in vehicles. Imagine a society where one could start their car inside of the garage without risk of asphyxiation. With some changes in the focus of the global energy market and investment by engineers and automakers alike, this imaginary society could become a reality in the near future.

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