Hydrogen-Powered Vehicles: A Future or Just a Dream?

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ABSTRACT

In this comprehensive review, the evolution of transportation sustainability is explored, focusing on the challenges and potential of hydrogen fuel cell technology as a viable alternative energy source. Beginning with an overview of the historical context, including the pioneering work of Sir William Grove in 1838, delving into modern advancements and challenges. From fundamental principles of hydrogen fuel cell operation to infrastructure requirements and safety considerations, industry trends, and modern technological advancements. Despite obstacles such as limited refueling stations and high costs, collaborative efforts among supporters of the technology hold promise for overcoming challenges and driving innovation forward. Ultimately, hydrogen fuel cell-powered vehicles represent a compelling pathway toward achieving a sustainable future in transportation.

Introduction

Throughout history, humanity has continuously sought improvement and innovation across various elements of life, including transportation. The evolution of transportation has been particularly noticeable, with significant advancements in recent years. For instance, the efficiency of cars reached the highest point, according to the United States Environmental Protection Agency, the fuel economy and horsepower of cars are at their all-time high, both increased by around 100% compared to cars in 1975. Moreover, car manufacturers are utilizing more advanced technologies, with 50% of the total population of cars carrying hybrid technologies and 59% installed with more than 7 gears ("The 2023 EPA Automotive Trends Report Greenhouse Gas Emissions, Fuel Economy, and Technology Since 1975," 2023). However, a continuously rising issue regarding environmental sustainability has emerged as a serious concern, with transportation being one of the major contributors to greenhouse gas emissions. In China, the emission causes an elevated level of fine particle matter (PM2.5) and ozone, resulting in up to 20,000 premature deaths annually attributed to traffic (Wang et al., 2023). As a result, this issue is driving the industry to a more sustainable way of travel.

In the 21st century, electric cars have gained increasing popularity, attention, and investment, alongside being promoted in many countries and industries as the solution for some of the negative effects of traditional fossil fuel-powered vehicles. In 2022, 10% of the total production in the United States are "strong" hybrid vehicles that can operate the car temporarily without engaging the engine; the amount of electric and plug-in hybrid vehicles increased from 4% of production to 7% of production within a year, and they are projected to increase faster in the future ("The 2023 EPA Automotive Trends Report Greenhouse Gas Emissions, Fuel Economy, and Technology Since 1975," 2023). Although being the frontrunner as a modern transportation alternative that increases environmental sustainability, they are not the only solution. A less polluting alternative called hydrogen fuel cells could also be a source of power generation for vehicles.

Despite their potential, however, they are not as well-known and remain relatively underexplored compared to other types of energy sources, such as electricity. On the other hand, hydrogen cars have a tank for 400 miles on average along with a shorter refueling time, making them more efficient than electric cars, which only have a range of around 100 to 350 miles. Therefore, this paper aims to provide a comprehensive review of hydrogen fuel cell-powered vehicles, which will include their historical development, current status, challenges, and the future of hydrogen-powered cars. From examining the statistics and insights from various sources, this review seeks to introduce the various potential and challenges of hydrogen fuel cell technology in the automotive industry and contribute to a more sustainable future.

Background of Hydrogen Power

Hydrogen fuel cells were first invented by Sir William Grove in 1838, when he put platinum electrons in a container of hydrogen and then into another container with oxygen and then immersed the system into a bath of sulfuric acid forming a single cell (Voss, 2019). He connected the cells into a series to form what he describes as a “gas voltaic battery”. He then wrote a letter about his invention to Michael Faraday, who was at the Royal Institution. This invention was published in the 1838 edition of *The London and Edinburgh Philosophical Magazine and Journal of Science* two months later. This is the first record of hydrogen fuel cells, thus Sir William Grove is known as “the father of the fuel cell”. Nearly one hundred years later, in the 1930s British scientist Francis Bacon believed in the usefulness of Sir William Grove’s hydrogen fuel cell invention and improved it by changing the electrolyte to potassium hydroxide and the electrodes to nickel instead of platinum (Flavell-While, 2018). A stable interface was established between hydrogen, oxygen, and the electrode using a pre-oxidized nickel electrode doped with lithium, making it a semiconductor. This greatly improved the fuel cell technology, and this technology was adopted by NASA, on the Apollo missions. In the 1960s, the proton exchange membrane technology was invented at General Electric, a technology that can greatly improve the efficiency of hydrogen fuel cells.

The advantage that hydrogen fuel cell technology has over most other alternative energy sources is its by-product which only contains water. The major disadvantage it has towards most other energy alternatives is that it is not comparatively well developed. Just as most other renewable energy sources the advantages and disadvantages to traditional fossil fuel are similar, so it would only be logical to compare the hydrogen fuel cell technology with other renewable energy. Electric battery-powered vehicles are used as a comparison to hydrogen fuel cell-powered vehicles since it is the most widely used renewable energy source. In most electric cars on the market as of 2024, batteries are used in the cars to store electricity which then powers the cars. As a result, the term electric vehicles (EVs) is used for vehicles that are powered with electric batteries, which would also be used in this article, meaning electric vehicles would refer to vehicles using batteries to store electricity.

The similarity between hydrogen fuel cell vehicles and electric vehicles is that they both use electricity as the power source, however, the way electricity is provided is different. Electric vehicles would have electricity plugged in and stored in their batteries, when the vehicle is operating electricity would be provided from the battery. On the other hand, hydrogen fuel cell-powered vehicles would have compressed hydrogen gas inputted into the vehicle (although very little carries liquid cryogenic hydrogen), when the vehicle is operating, the fuel cell would run and generate electricity with the compressed hydrogen and power the car. The advantages of hydrogen fuel cell cars over electric cars are that they have a much faster refueling speed and offer greater driving range (Moseman, 2023). The refueling experience of hydrogen fuel cell-powered vehicles would be similar to gasoline, resembling a “pump-and-go” experience. On the other hand, electric vehicles are more developed, with a more mature infrastructure such as the quantity of charging (refueling) stations, and more manufacturers and models to choose from.

Fundamentals of Hydrogen Fuel Cell Technology

Hydrogen fuel cell technology is one of the most widely discussed energy sources due to its clean nature. It offers a promising solution for sustainable transportation and power generation. This section will provide an overview of the principles behind this hydrogen fuel cell technology and its operation. Unlike batteries, hydrogen fuel cells are an electrochemical device that transforms chemical energy in hydrogen into electrical energy. On the other hand, electric batteries store the energy and use it when needed instead of generating the energy. The basic components of a hydrogen fuel cell system consist of a fuel cell stack, hydrogen storage tank, oxygen supply, and a power management system, each playing an important role. Although hydrogen is the 3rd most abundant element on Earth, it rarely exists on its own (*Hydrogen – the Number 1 Element*, n.d.). Most of the time hydrogen exists in the form of compounds, with the greatest quantity found in water, and also commonly found in hydrocarbons. As a result, a process is needed to extract hydrogen from those compounds. One of the processes is called steam reforming, a commonly used industrial process that produces hydrogen from hydrocarbons under a high temperature. A typical reforming reaction using steam (carbon dioxide can also be used) would have an equation: $CH4 + H2O \rightarrow CO + 3H2$. To increase the hydrogen yield, another reaction called the water-gas shift reaction with an equation: $CO + H2O \rightarrow CO2 + H2$ would also be performed. Additionally, the water-gas shift reaction is exothermic, as a result, it provides some energy for a reforming reaction which is an endothermic reaction requiring large amounts of energy input, as a result, the steam reforming reaction is only 65-75% efficient (New York State Energy Research and Development Authority, 2006). Additionally, all the carbons in this process in the inputted methane would eventually become CO2 creating a carbon footprint, making this a less ideal option since it does not align with the goal of sustainability. The other way to produce hydrogen is from electrolysis, which uses electric current to separate hydrogen from water. This process still requires energy input for the current which decreases the efficiency of the process.

However, there is a more efficient method to generate electricity using a proton exchange membrane (PEM). This process requires water to be separated into hydrogen and oxygen first using electrolysis, where the hydrogen produced would be placed at the cathode and the oxygen produced would be placed at the anode. The hydrogen at the cathode would be in the form of protons (H+) and electrons (e-), and protons would flow through the PEM to react with the oxygens, however, the PEM does not allow the electrons to go through, as a result, the electrons would flow through the wire, creating current and electrical energy. With this combination of proton exchange membrane and electrolysis, the efficiency is 80% on a low heating value basis, however, this technology is still progressing and is expected to reach better efficiency in the future (*Electrolysers - Energy System - IEA*, n.d.).

Due to the lightweight and low-density nature of hydrogen, hydrogen is stored in two ways to ensure efficient storage. The first way is to store hydrogen in the form of compressed gas. This process would compress hydrogen to about 790 atm, so it reaches a high energy-to-volume ratio. The other method is to store hydrogen in liquid form, this requires hydrogen to be cooled cryogenically to a temperature of -253°C. Then it would be stored in insulated tanks to maintain this low temperature and avoid evaporation. Both methods require energy to be inputted into storage, however, the second method requires more energy since the temperature has to be dropped to -253°C to liquefy. For context, hydrogen is the second hardest gas to liquefy, only behind helium.

Infrastructure Requirements and Challenges

Many challenges would be faced in popularizing hydrogen fuel cell-powered cars, with one of them being infrastructure requirements. Each type of energy source has its way of refueling, and it is an important factor that would be considered by the customers. Traditional fossil fuel-powered vehicles utilize gas stations that pump in gasoline and diesel, and electric cars utilize charging stations. Charging stations are crucial to the success of electric vehicles because they allow customers to charge in their own parking lots, malls, stadiums, etc. As a result, the customers would not have to worry about the issue regarding refueling, and hydrogen fuel cell-powered vehicles would have to do the same to achieve success in becoming mainstream. According to the US Department of Energy, there are 59 operational retail hydrogen stations in 2023, and there are at least 50 more hydrogen refueling stations that are in various phases of planning or construction (*Alternative Fuels Data Center: Hydrogen Fueling Stations*, n.d.). Highlighting that the amount of hydrogen refueling stations is limited compared to the refueling stations of other power sources.

Another problem that would have to be solved is the concerns associated with safety and high costs. The concern regarding the safety of hydrogen is the highly flammable nature of the gas. Hydrogen gas burns in the air when the concentration is between around 4 to 75%, therefore, if it is not used properly it may cause fires and explosions (*What Are the Pros and Cons of Hydrogen Fuel Cells?*, n.d.). To prevent the danger from mixtures of air and hydrogen, smoking close to any area where hydrogen is used or generated should be avoided. Additionally, all potential sources of sparks and flame should be removed. Additionally, the only place where hydrogen should be used is an outside place where there is enough ventilation to adjust the excessive concentration of hydrogen in the atmosphere (*Hydrogen Safety*, n.d.). The other problem is the overall cost of hydrogen as an energy source. As of 2023, hydrogen energy is more expensive than other energies such as fossil fuels. The reason for this cost is the comparably less energy per unit volume to fossil fuels, high energy taken to extract hydrogen, transportation costs, and the precious metals such as platinum and iridium that are required for the hydrogen fuel cells as catalysts and sometimes water electrolyzer. Based on a report from the US Department of Energy, through the different processes mentioned above, these expensive costs of hydrogen will exceed the cost of gasoline on a per-gallon equivalent basis which will likely make it unattractive to consumers.

Greater support and investment would be needed for the success and adaptation of wide-spreading hydrogen fuel cell technology in transportation. Problems such as costs can be resolved from an increased demand for hydrogen-related products. Organizations such as the H2USA have been focusing on expanding infrastructures for hydrogen to provide consumers with more energy options. On the other hand, industrial leaders such as Toyota, have started creating models of hydrogen cars to bring it to reality, which bridges the gap between innovation and reality, thereby advancing the progress of the entire industry. As adaptations continue, safety concerns can be regulated well with newly implemented laws as the use of hydrogen fuel cells increases to prevent possibilities of danger. From the collaborative support and efforts from different groups, including government, manufacturers, and proper publicization and education to the public this technology can mature sooner and achieve the goals of environmental sustainability.

Environment Concerns and Market Trends

In previous sections, it is noted that hydrogen does not provide a competitive efficiency for now, which then creates an excessive cost that consumers would be hesitant to spend. However, this technology is still being considered due to its environmental benefits. The potential is mainly seen from the end use when the fuel cell generates electrical energy with the only by-product that would be emitted in that process being water. This leads people to the idea that hydrogen is a completely environmentally friendly alternative. However, that is not entirely true, since hydrogen would have an environmental impact in other stages using current methods. For example, a prominent contributor to this environmental impact resides in the energy-intensive process of hydrogen extraction. If this energy is not produced from sustainable sources, there exists a substantial risk of environmental pollution as a consequence. Another example is in steam methane reformation, where a by-product of carbon dioxide contributes to the carbon footprint of this process. Additionally, if the transportation and storage required by hydrogen use energy from sources such as fossil fuels to power, pollution would still be made. Moreover, in the transporting and storage process air pollution is caused when hydrogen is leaked. At last, waste disposal could also be a concern, during the production of hydrogen catalysts are used and byproducts are created and they should be handled properly to avoid soil, water, or air pollution.

As of the end of 2022, approximately 56000 hydrogen-powered passenger vehicles were sold worldwide, with 30,000 of those being hydrogen fuel-cell vehicles (FCEVs) that are sold in 2021 and 2022 (Hunt, 2023). Studies have shown a growth in the market of hydrogen, in 2023, hydrogen generation was valued at $158.8 billion, and the market is expected to reach $257.9 billion by 2028. This is a growth of 10.2% in compound annual growth rate. Additionally, this market is widely supported by the public, as shown in a report by Bosch, among all respondents thirty-three percent of those surveyed think hydrogen would improve society, and 82% of all respondents believed that sustainable companies will succeed financially, which shows that the public is also aiming for a more sustainable future (*New Study Finds That the Public Favors Hydrogen | FASTECH*, 2023). Although public support is important, one of the most important catalysts to the success of renewable energy is the support of governments. In China, the policy for hydrogen is to increase the production of hydrogen from renewable energy sources to 100,000 to 200,000 tons per year by 2023, with hydrogen being a significant portion market (Peng & Ren, 2023). In Germany, the plan by FNB for hydrogen is to reach a demand of 71 TWh by 2023 (FNB Gas, 2021). On the other hand, according to the National Hydrogen Council's "Hydrogen Action Plan Germany 2021-2025," the industrial sector (excluding refineries) will demand 57 TWh of hydrogen, and the mobility sector will demand about 25 TWh of hydrogen. A majority of this hydrogen is used directly in fuel cell electric drive forms (Nationaler Wasserdtoffrat (The National Hydrogen Council), 2021).

However, another huge potential problem that might influence the improvement in this technology is the other markets that would be threatened by the advancement of this technology, with the largest one being the fossil fuel industry. As of 2022, the global fossil fuel market size is USD 4.2 trillion and is expected to increase to USD 11.78 trillion by 2032 ("Fossil Fuels Market Size to Hit USD 11.78 Trillion by 2032," 2023). This market is a lot larger than the hydrogen fuel cell industry, which is only valued at 158.8 billion, a difference of around 75 times. However, with the rise of other renewable energy sources, the market for fossil fuels would not be able to grow as it originally did. As a result, voices of the fossil fuel industry suppressing the growth of other alternative energy sources, including hydrogen fuel cells, rise. One of them is the Union of Concerned Scientists, which has accused fossil fuel companies of intentionally spreading disinformation about the climate for decades, with company leaders being aware of the harmful effects of their products but choosing to deceive the public and deny this harm, at last, the "campaign of deception" continues to this day (*The Climate Deception Dossiers*, 2015). This is done by forged letters to Congress, secretly funding and supporting independent scientists, establishing fictitious grassroots organizations, etc.

Recent Technological Advancements

Hydrogen fuel cell technology has its downsides and challenges, however, like many other technologies, it is constantly improving. One technology that greatly benefits hydrogen production is electrolyzers, a machine that separates water to produce oxygen and hydrogen through electrolysis. In the market today, we have larger and commercial electrolyzers such as Siemens Silyzer 300, they adopt the proton exchange membrane (PEM) technology to produce ultra-pure hydrogen with very little oxygen gas, a concentration of less than 100 ppm (Sebastian et al., 2023). Renewable energy sources power the latest commercial electrolyzers, offering the flexibility to operate at partial loads while incorporating improved heat exchange systems. These advancements enable the new electrolyzers to produce cleaner hydrogen, conserve energy, and extend their service lifespans. At last, many details in electrolyzers made improvements, such as the flow of water through the PEM fuel cell, or using an anion exchange membrane instead.

According to Sebastian et al., the car manufacturer Hyundai has implemented a combination of lithium-ion batteries and hydrogen fuel cells to reduce the disadvantage of low energy-to-volume ratio in hydrogen fuel cells. The higher energy-to-volume ratio from combining hydrogen fuel cells with lithium-ion batteries can be crucial due to the small space provided in cars, an advantage like this can greatly increase the appeal of this technology. While other car manufacturers took a different approach, NamX HUV introduced a removable setup to reduce the refueling time of hydrogen fuel cell vehicles (2023). This technology can also effectively solve problems that could disadvantage the hydrogen fuel cell technology, with a removable setup, consumers would not receive more inconvenience as it is similar to other manufacturers' approach with electric vehicles. These developments reflected the efforts made to overcome the barriers to adopting hydrogen fuel cell technology into the automotive industry.

Storage is another improvement that can greatly improve the application of hydrogen fuel cells. There are multiple ways that hydrogen can be stored, it can be in liquid, gas, and hydrides. Hydrides are a complex solid-state material that is a compound of hydrogen and other metallic elements. Magnesium hydride is one of the considered choices to store hydrogen since it offers a high capacity, simple nature, and low cost, however, the operating temperature of the storage is around 600 K, making it unsuitable for hydrogen storage (Grant, 2008). As a result, the solution of storing hydrogen in the form of metal hydrides would still have to be further developed. Currently, the most widely used method to store hydrogen is by compressing hydrogen gas up to 350 to 700 bars and storing it in a gas tank (*Hydrogen Storage*, n.d.). This method does not require cryogenic temperatures that are needed when storing hydrogen in a liquid state due to its boiling point. Additionally, compressed hydrogen gas offers the highest energy density of approximately 120MJ/kg, which is nearly three times higher than diesel and gasoline. In terms of electricity, diesel only contains about 12-14 kWh of usable energy per kg, but hydrogen has an energy density of 33.6 kWh.

Case Studies and Real-World Applications

Although car manufacturers tend to develop electric cars first, some still believe that a hydrogen fuel cell is a viable option and have developed it. Toyota is a good example since they produced the Toyota Mirai, the first mass-produced hydrogen fuel cell vehicle(Influx, 2023). The 2024 version of Mirai can provide a horsepower of 182kW and a range of 647 km (*2024 Toyota Mirai Specifications & Models | Toyota Canada*, n.d.). Not only does the car have these specs, but it also has a global sale of 21,475 as of November 2022 (Corporation, 2022). Even though private cars are a huge market, hydrogen vehicles have quite a big market in public transportation. As mentioned by Ashley Hancock, in 2022 the market for hydrogen buses globally is valued at 7.8 billion USD and its estimated valuation for 2023 is 49.2 billion USD, with a compound annual growth rate (CAGR) of 30.1% throughout this time, additionally, many large cities have already implemented hydrogen buses in their transportation, including London, Paris, Tokyo, Shanghai, and others (2023).

The successful experience of hydrogen fuel cell technology in public transportation is largely due to governments' regulations and expectations of environmental sustainability. One example is the European Union, the European Commission proposed reducing carbon emissions in heavy-duty vehicles from 2030 onwards, to reduce 90% of carbon emissions by 2040 (Strasbourg, 2023). This greatly benefits hydrogen-fuel vehicles which emit water instead of carbon dioxide into the atmosphere. A review from Motor Trend pointed out some of the problems of the Toyota Mirai, for example, less range than Toyota promised, and problems with hydrogen-related infrastructures. On the other hand, the benefit is the fuel price, which is maintained stably even when gasoline prices rise (Gold, 2022). Furthermore, in a 2023 report from Bosch, 33% of participants in its global survey believe that hydrogen fuel cell technology can make a particular contribution to society ("We Asked The World: What Do People Around the World Think and Feel About Technology," 2023).

From the example of the Toyota Mirai and municipal buses, it's shown that there is a market for hydrogen-powered vehicles However, they are not well developed to reach the same level of convenience as traditional fossil fuel-powered vehicles and even electric vehicles. However, some in the public and experts are optimistic about hydrogen cars benefiting society in the future and the government is getting increasingly strict in regulations regarding carbon emissions. These conditions suggest a bright future for hydrogen fuel cell-powered vehicles as long as improvements can be made. From the examples above it's clear that hydrogen infrastructures have to be improved and with more production of hydrogen fuel cell-powered vehicles, the prices would also drop making them more accessible to society.

Future Outlooks and Applications in Aviation

The challenges now faced by the hydrogen fuel cell industry are mainly on how to improve this technology so that it is a sustainable yet efficient source of energy. The easiest and fastest way to overcome all these challenges is through government support and regulations, with the help of the government restricting the competitors of hydrogen, and subsidizing the industry and the consumers using hydrogen technology. This can be accomplished due to the trend of creating an environmentally sustainable future, which nearly every country promotes. As a result, it is realistic to use governments to the advantage of the advancements in technology and industry. Once hydrogen fuel cells become an energy that can practically replace fossil fuels and electricity, with a lower cost and higher efficiency, it is possible to have a future with hydrogen-powered vehicles.

Other than cars, where hydrogen fuel cells are mainly used, the aviation industry could be a better fit for this technology. Aviation contributed 2% of energy-related CO_2 emissions globally in 2022, however, airplanes not only release carbon dioxide emissions, they also have a significant non-carbon impact on the environment. This resulted from the nitrogen oxides, which are created because at the high operating temperatures from the engine, oxygen, and nitrogen particles in the air would join together forming nitrous oxides, with the form of NO_X (NASA Glenn Research Center, 2023). These are some key contributing factors to climate change, according to the U.S. Environmental Protection Agency, one pound of N_2O (nitrous oxide) is 265 times more impactful in the warming effect on the atmosphere than 1 pound of carbon dioxide (2024). Another effect of global warming is contrails, which are man-made clouds formed from condensed water vapor, they absorb and trap solar radiation from the sun that is traveling to space within the earth's surface causing global warming. As a result, combining both the effects of all emissions and water vapor trails from planes, the industry contributed to about 5% of global warming worldwide, making planes the transportation that creates the most pollution, only after cars which have a much larger quantity.

As a result, a new renewable energy source alternative is needed to be used for the aviation industry to improve the sustainability of the environment with hydrogen fuel cells being one of the potential alternatives. The biggest advantage of using hydrogen as the onboard fuel is the complete elimination of carbon dioxide emissions in flight, which can greatly reduce carbon emissions in total and is the main reason that might cause the industry to shift to a new energy source. The second advantage is the lightweight nature of hydrogen, in aviation lightweight corresponds to less energy being used and more efficient travel, as a result, with lighter fuel energy unnecessary energy usage can be avoided. However, the efficiency of the fuel remains a problem, the energy of jet fuel molecules is four to eight times more than that of a hydrogen molecule, meaning that more fuel would be needed to be carried when using hydrogen as the carried fuel (TWI Ltd., n.d.). A solution would be to improve the efficiency of fuel cells to create more electricity or compress hydrogen even more to make up the difference in efficiency. Another issue with powering airplanes with hydrogen is that more water vapor is now produced, which would still contribute to global warming. Nevertheless, the development of hydrogen-fueled aircraft has received major financial support from numerous countries and companies and has a good chance to be the future of the aviation industry (Yusaf et al., n.d.).

Conclusion

In conclusion, the evolution of transportation has witnessed significant advancements, in particular sustainability. While electric battery-powered cars have emerged quickly in these few years as the modern transportation alternative for a sustainable future, hydrogen fuel cell technology also delivers itself as a promising solution with its advantages including faster refueling time and greater travel range. Originating from more than centuries ago by Sir William Grove, hydrogen fuel cells have gained multiple significant improvements over time, such as better choice of electrode, electrolyte, and the invention of the proton exchange membrane that would only allow protons to pass through. However, many practical problems have still not been resolved, notably the lack of infrastructure for refueling vehicles, generating hydrogen, storing hydrogen, and transporting hydrogen. Improving these elements would be crucial when hydrogen fuel cell vehicles are made for wide public use. These challenges with infrastructure cause inconveniences for the user and the increased cost of operating hydrogen cars, which would decrease the appeal for hydrogen fuel cell-powered vehicles. On the other hand, these problems would be easily resolved if hydrogen is a more widely used energy source, making this situation self-sustaining. Additionally, hydrogen is a sustainable energy source that aligns with the major trend of this decade, and as a result, the hydrogen industry can rely on government support and investments to reach the goal of improving basic infrastructures.

The trend in the market for hydrogen cars is still increasing, along with the expected increase in the fossil fuel market. As a result, competition between energy sources would be created, which is a disadvantage for the hydrogen fuel market due to the huge difference in market size. However, many corporations still favor the new hydrogen fuel cell industry by investing in and even developing the technology themselves. One of the companies that developed the hydrogen fuel cell technology on their cars and sold it in the market is Toyota. Its success with the Mirai shows the potential of this technology and introduces it to more people and manufacturers. Under the continuous development of technology, hydrogen is closer and closer to being a practical energy source in the automotive industry, with better efficiency, and different technologies that the manufacturers can choose from to benefit their vehicles. Although still mostly in experimental stages, hydrogen would also be a good fit in the aviation industry with its lightweight and pollutionless nature, nevertheless, the disadvantages remain, including other types of potential pollution and efficiency issues. Despite the challenges that would be faced by implementing hydrogen fuel cell technology into the aviation industry, a large number of investments were still put into the projects.

For customers who are willing to purchase hydrogen vehicles, as of now, the vehicles do not show significant advantages to other energies but rather show multiple disadvantages. Looking ahead, the future of hydrogen vehicles still appears to be promising, especially with increasing awareness and efforts related to climate change globally. Government initiatives combined with advancements in research and development, would pave the way for hydrogen vehicles to play a more pivotal role in achieving a more sustainable and environmentally friendly transportation landscape. With more innovation and collaboration of scientists, engineers, entrepreneurs, and the public, hydrogen vehicles can hold the key to a more environmentally sustainable future without carbon emissions and beyond. Technology has never stopped advancing and most people are all united to the same goal of a more sustainable future. To obtain this goal hydrogen should be continuously developed and supported so that one day there will be another choice for humans in sustainable energy.

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