

# Hydrogen Fuel-cell Technology in Electric Vehicles: Current Usage, Materials and Future Applications

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**Abstract.** A conventional combustion engine results in high greenhouse gas emissions, so the world is transforming to clean energy and electric vehicles. Developments and applications of hydrogen fuel cells in electric vehicles (EVs) lead the world toward a sustainable future. Hydrogen fuel applies to fuel cells and generates electricity through electrochemical reactions. It is exceptionally clean because the by-products are water and heat, so there has no visual pollution from vehicles. HFC technology is not commonly used for now but will take place in many EVs. Some countries planned to apply it to electric power systems, railways and spacecraft fields. Currently, HFC uses platinum as the main catalyst material because of its stability, high efficiency, and good performance that boosts the hydrogen and oxygen reactions. It is the most reliable source and a perfect catalyst that is widely applied. Other catalysts such as carbon-coated nickel, nitrogen-carbon mixtures (MNCs) and transition metal nitrides (TMNs) all show good performance and have similar efficiency with Pt. These materials could replace platinum in the future because Pt has limited sources and higher costs. Also, the study has found that scientists use ruthenium graphene as a catalyst in hydrogen fuel cells. However, its effectiveness needs long-term monitoring. Although HFC is a clean technology, it has disadvantages, for example, hard for hydrogen extraction and storage, lacking refueling systems etc. Current technology limits development, and barriers exist, such as overwhelming H<sub>2</sub> storage and delivery and some safety issues. Even so, hydrogen energy and HFC application are the future for EVs and others.

**Keywords:** Hydrogen Fuel Cell, Electric Vehicles, oxygen reduction, Hydrogen Oxidation, Hydrogen Storage and Refueling.

## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) suggests the world keep global warming to no more than 1.5 °C. Note that 189 nations have signed the Paris Agreement. They aim to achieve a 45% reduction in emissions by 2030 and be carbon neutral in 2050 [1]. This climate action pushes the world to increase investment in renewable energy and technology for a green economy and sustainable future. CO<sub>2</sub> is the most common greenhouse gas produced by conventional cars because of the burning of fossil fuels and gasoline. Therefore, electric vehicle development is the optimal way to reduce emissions. Countries pointed out the Zero-Emission Zone with emission regulations, such as the City of Los Angeles in the United States. However, it never works alone. Transforming on fuels is important. Hydrogen fuel is cleaner compared to fossil fuels (ICE). Currently, hydrogen fuel cell technology has been applied in some ranges such as cars, trains, spacecraft, marine vehicles, power generation etc. Its effectiveness is generally defined as zero-emission, short time for charging, scalable, and high efficiency (40-60%) compared to ICE [2].

Hydrogen fuel cell plays an important role in the electric vehicle field. The material selection is also important because it determines the fuel cell's efficiency, storage, costs, and long-term effectiveness. For now, the main source used in hydrogen fuel cells is platinum, a perfect catalyst for ORR and HOR reactions; Pt helps to boost reactions at an optimal rate. However, platinum is very scarce on Earth, so it is necessary to find substitutes, which would be a challenge [3]. In this research, the design principle and the usage of hydrogen fuel cells have been carefully summarized.

Meanwhile, the catalyst materials used for hydrogen fuel cells are compared, including Pt-substitute sources. And then, its advantages and disadvantages are briefly defined, especially the

current obstacles to the commercialization of hydrogen fuel cells are also discussed. Moreover, the importance of using HFC in EVs is mentioned; its future applications are also summarized.

## 2. The basic information about hydrogen fuel cell

### 2.1. Fuel cell and hydrogen fuel cell

In the past few years, industries invested in battery-powered vehicles such as Lithium battery-electric cars, and it has become the most popular EVs in the world. However, lithium battery EV has a relatively shorter lifespan because batteries need replacement after mileage driving [4]. Fuel cell technology is the world's solution to emissions because FCs are more efficient and cleaner than others. It converts chemical energy to electricity and works like batteries, but additional charging is not required. The FC can keep producing electricity as long as hydrogen fuels are sufficiently and continuously supplied.

Fuel cells contain several types and most required hydrogen fuel to power up devices, such as the alkaline fuel cell (AFC), phosphoric acid fuel cells (PACs), direct methanol fuel cells (DMFC) and polymer electrolyte membrane fuel cells (PEMFCs) etc. These fuel cells belong to hydrogen fuel cells, and the only by-product produced is water during electricity production [5].

This paper mainly focuses on applying PEMFCs, most applied to primary transportation, including cars, trucks, planes, and railways, and some for stationary use. Currently, hydrogen fuel cells are used on electric vehicles such as Toyota Mirai and Hyundai Nexo. And there will be more hydrogen-powered automobiles in the next five to ten years. For example, the BWM and Land Rover are planning their new models of EVs and vans powered by hydrogen fuel cells [6]. Also, China has claimed to develop more hydrogen refueling stations to reach about 1000 by 2030 and wider the hydrogen fuel cell market [7].

### 2.2. Principles and composition of hydrogen fuel cell

A fuel cell comprises two electrodes, an electrolyte, and a catalyst layer. Electrodes contain two sides. One is the negative side known as the anode; another is the positive side as the cathode. For a hydrogen fuel cell, hydrogen is applied on the anode side, and air passes through the cathode side. Platinum is a catalyst and applies to the anode side that separates the hydrogen atoms into protons and electrons. These will deliver into different paths to the cathode sides. H molecules separate electrons, and electrons then pass through an external circuit to create electricity flow; the protons pass the electrolyte to reach the cathode side, producing water and heat through electrochemical reactions that ally with oxygen and electrons [8]. It shows in a simple equation:

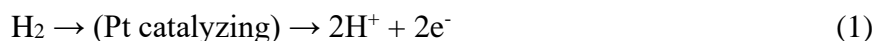
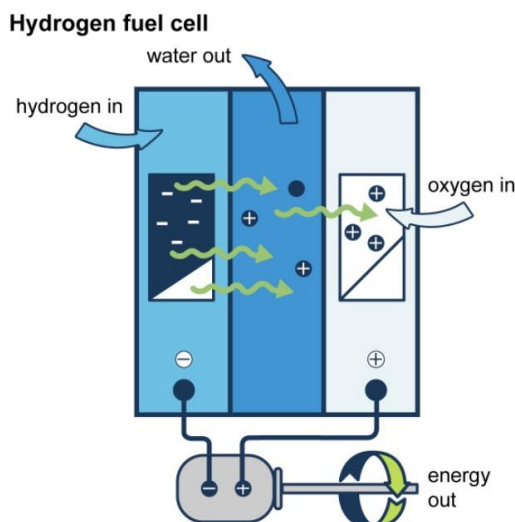
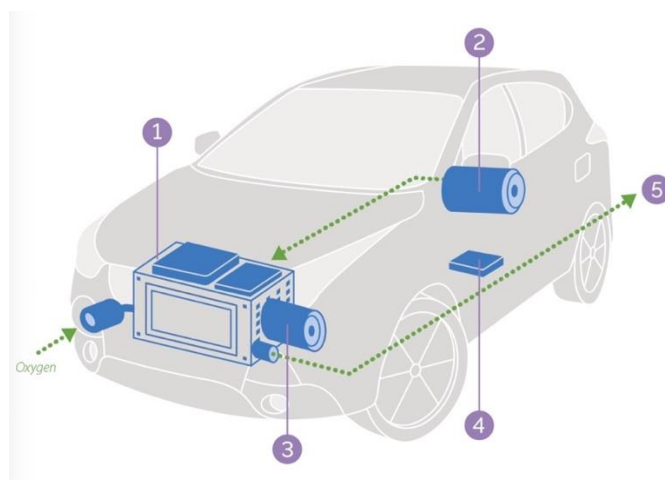


Figure 1 below illustrates the process within the cell that which hydrogen molecules and electrons pass way in a hydrogen fuel cell, with water as the by-product emitted out and electrical energy produced from the cell.



**Figure 1.** Hydrogen Fuel Cell [9]

Currently, the world is pushing toward the hydrogen economy, applying hydrogen fuel cells to wider use, such as the implementation of hydrogen-powered electric vehicles, marine vehicles, power generations, houses, mobile power and so on. For example, an electric car powered by a hydrogen fuel cell (Figure 2) works in the way that the cell compresses hydrogen with gas status and feeds into the stack, which does not burn the gas but converts hydrogen fuel energy into electricity through electrochemical reactions. Finally, the electricity produced will power the car and enable its electric motors to run [9].



**Figure 2.** Hydrogen Fuel Cell Electric Cars [10]

Figure 2 above is a hydrogen-powered E-Car with five main parts highlighted in numbers. Number 1 is the Fuel Cell Stack where oxygen and hydrogen are combined to produce electricity and power the motor; number 2 is the Fuel Tank, a place to store hydrogen gas and provide hydrogen to the Fuel Cell Stack. It is usually made of carbon fiber, aiming to reinforce the tank for hydrogen gas storage. Number 3 is the Electric Motor for powering the car, and Number 4 represents the Battery, providing additional power to the electric motor and capturing energy. Number 5 is known as Exhaust, a place to discharge by-products out. A hydrogen-powered E-car only produces water and heat so that water will be emitted through the Exhaust, and it is a process that achieves zero-emission.

### 2.3. Advantages of the hydrogen fuel cell

Zero-emission is the main goal for the world to start investing in hydrogen energy and fuel cell technology. There are other prominent effects of HFCs compared to diesel engines or ICEs. First, it is very efficient because hydrogen is an environmentally friendly source. It only produces heat and water as an energy carrier for electricity generation. The process usually operates with higher

thermodynamic efficiency, almost 60%. To note that an internal combustion engine could only achieve 30% efficiency, a Polymer Electrolyte Membrane (PEMs) enables to have 50-60% when applied on transportation; and an Alkaline Fuel Cell (AFCs) has an efficiency of 60-70% and is currently applied to military and space uses. These fuel cells show good part-load performance and are perfect for cars, trucks, and spacecraft use. They operate through an electrolysis process at a lower temperature, around 80 °C compared to others, faster and more durable than ICEs [11]. Second, HFC-powered cars are shorted in refueling time and have longer lifetimes than gasoline and other battery cars. It only takes about 2-3 minutes to charge, which is very convenient. Lithium battery-based E-cars take 1 hour to 12 hours for charging, requiring a recharge after long driving mileage, usually between 5 to 10 years range. Research has investigated that the lifecycle of HFC vehicles is longer than ICEs and battery EVs. Because HFCs are lower in energy consumption and GHGs emission when driving and faster in refueling time [12]. Next, hydrogen is the most abundant element in the universe, and it is a renewable fuel source than others such as coal and petroleum. Currently, hydrogen fuel is the leading source of renewable energy storage and sustainable development. Moreover, driving an HFCV has no visual pollution because it only produces water and heat, and it is lower in noise pollution because the car's weight is light and has no internal combustion engine inside. Also, a hydrogen fuel cell does not have moving parts, requires extraordinarily little maintenance and is more reliable than other cars such as gasoline and battery-based E-cars [13].

#### **2.4. Disadvantages of the hydrogen fuel cell**

However, HFCs do have some disadvantages. First, it is hard to extract hydrogen molecules, although hydrogen is abundant in the universe. Because the H molecule always bonds with others, such as oxygen and carbon, it requires huge energy and highly technical support for extraction. Second, total and material costs are higher because it requires catalysts to boost oxidation-reduction reaction and the main source for catalyzing is platinum. It is the most expensive material used in a hydrogen fuel cell, resulting in higher costs and market prices. And then, hydrogen is extremely low in density and easily dispersed in the air, so it is hard for storage and delivery. Technology is the main issue in dealing with the problem, and industries must avoid hydrogen leakage and maintain its purity when delivering. Currently, hydrogen is being compressed into gas, liquid, and solid states for storage; high-pressure gas cylinders, cryogenic tanks and pipelines are used in H<sub>2</sub> storage and delivery. Also, its inflammability often raises additional costs, so more advanced technology is needed.

Moreover, hydrogen refueling infrastructures are lacking because other primary energy resources, such as oil and gasoline, have been used for decades and are seen as the base. Transforming to hydrogen fuel cell-based development requires a supply of many newer refueling stations and network systems. But hydrogen is very inflammable and often dangerous to the public. Also, it might cause electric shock. For example, some motors run at about 350V, often higher in currents; it is more likely for the electric shock to happen and even cause life danger. Hence, it is awfully hard to establish hydrogen refueling stations at the current stage. Safety issues are a major concern [14].

### **3. Materials for hydrogen fuel cell**

The hydrogen fuel cell contains the oxygen reduction reaction (ORR) and hydrogen oxidation reaction (HOR). Currently, hydrogen fuel cell for commercial use relies on the ORR reaction, which separates O<sub>2</sub> molecules into oxygen ions. Then the ions will combine with protons to form water. It is part of converting hydrogen and oxygen in the air into water and electricity. ORR slows the reaction, limiting fuel efficiency; therefore, a large amount of platinum catalyst is needed. Platinum is the main source required for making a hydrogen fuel cell, such as PEMFCs, which are used in transportation, like EVs. A fuel cell consists of five main parts: catalyst layers, cathode side, anode Side, electrolyte, and gas diffusion layers; the materials used for each part are different but mainly come from platinum and act as a catalyst.

### 3.1. Catalyst materials

Platinum represents a catalyst in the hydrogen fuel cell. It has been widely used at the catalyst layer and the Anode and Cathode sides. These are places where the electrochemical reactions start, reactants  $H_2$  and  $O_2$  molecules being split into electrons and protons, and the ORR taking place at the cathode side. Materials for the catalyst layer, including nanometer-thin platinum and carbon paper, are the common sources for current applications. Because a catalyst layer needs to be highly effective when splitting molecules into electrons and protons, it is the thinnest place in the fuel cell, about 5 to 30 microns [15]. Pt is applied to the catalyst layer for reactions and molecule separations, it is an incredibly good catalyst that could stand for very high temperatures and hold up under acidic conditions compared to other metals such as nickel, and the process produces only water and heat during reactions, nickel might produce a little methane as a by-product. Platinum is the most efficient catalyst for a hydrogen fuel cell and is the material used to boost hydrogen oxidation reactions for the anode side.

Meanwhile, carbon-coated nickel is also an essential material for catalyzing reactions. An electrocatalyst is applied to form a protection layer at the surface. It is nickel-based along with a 2-nanometer nitrogen-carbon mixture shell [16]. Nickel-based catalysts get similar efficiency compared to the application of Pt. Moreover, research has found that in China, scientists used ruthenium-graphene to replace platinum as a catalyst for hydrogen fuel cells; because Pt is expensive, industries are seeking Pt-substitute materials for durable and sustainable development. The study has found that ruthenium-graphene shows higher tolerance to acidic conditions and is better than Pt-fuel cells. It might be commonly used in the future, although its long-term effectiveness requires monitoring [17]. Even so, platinum is still the most efficient catalyst. However, future development requires other resources to replace platinum due to its patterns.

To replace the platinum, scientists are moving to find other substitutes, including iron, nitrogen-carbon mixture (MNCs), and transition metal nitrides (TMNs). These materials will be used as catalysts, for example, by mixing iron, nitrogen, and carbon elements and heating them between 900 to 1100 Celsius degrees under pyrolysis. After heating, iron atoms bond to nitrogen atoms and at the state that enables the ORR reactions to occur [18]. Also, using TMNs as a catalyst would be more effective if a thin oxygen-based layer formed an outer shell to provide a perfect surface for chemical reactions and conduct electricity when exposed to air. To achieve platinum-free catalyst transition, scientists need more time to prove its long-term effects and pursue higher efficiency for future applications in FCEVs.

### 3.2. Other materials

Excepting the main reaction parts, materials used for electrolyte, gas diffusion layers, and hardware also contains platinum, but not as the main source. First, the material used for the electrolyte contains Nafion, or Perfluoro-sulfonic acid [19]. It is the place between two reaction sides to conduct hydrogen ions; the electrolyte contains an inner metal such as tantalum and is usually filled by concentrated NaOH solutions. Hydrogen fuels and oxygen are filled in the electrolyte through electrodes, reactions start, and water forms. Second, the gas diffusion layer is the place to conduct reactants into the catalyst layers. Carbon paper is the most common material used to make it, carbon fiber is often coated with PFTE, and the layers are usually coated with Teflon to move wastewater out. Its inner surface is always coated with a high surface area carbon mixed with PFTE, used to adjust water release from pores and retention of the membrane to maintain conductivity and enable  $H_2$  and  $O_2$  to diffuse into two electrodes.

Moreover, hardware is also an important component of a hydrogen fuel cell because it helps to make membrane electrode assembly operate effectively. Hardware comprises gaskets and bipolar plates; gaskets are made of silicone rubber and usually at the edges of the MEA; the bipolar plates are made of graphite and other metals such as aluminum, steel, and titanium. It helps to provide conduction between cells and allows gases to flow into the MEA. It usually clips the cell to separate it from others.

To sum up, platinum is the main material used for a hydrogen fuel cell, and it is a perfect catalyst for side reactions. However, platinum sources' rarity and higher operating costs limit the commercialization of hydrogen fuel cell EVs, forcing industries to transform to platinum-free or platinum-substitute materials for making a hydrogen fuel cell. Iron, nitrogen-carbon mixture, ruthenium-graphene, and transition of metal nitrides are all substitutes, and they all show particularly good performance in the process, especially the TMNs and MNCs [20]. The study has found that TMNs show strong interactions with other absorbates and are greater in reaction activity, selectivity, and stability. Meanwhile, MNCs have also been a good catalyst in fuel cell reactions. It shows the most promising activity and better ORR reaction performance because it has bigger atom utilization and stability. Both TMNs and MNCs could replace platinum as fuel cell catalysts in the future due to their performances and relatively lower costs. However, it is still crucial for the public to accept this advanced technology; identically, challenges of applying TMNs and MNCs also exist. But considering long-term efforts, material and operational costs, and level source scarcity, TMNs and MNCs are more suitable for future EV applications; efficiency is relatively the same for platinum-based and transition metal-based catalysts.

#### **4. Hydrogen fuel cell performance on electric vehicles**

This paper mainly focuses on applying hydrogen fuel cells in the sector of on-road electric vehicles, including cars, trucks, and public buses. Currently, HFCs are commonly planned to use in the EV sector because they are small and have zero emissions. Some battery-based electric vehicles are transforming into hydrogen-powered EVs in the future, and most conventional combustion engine-powered cars will be replaced from the market; the European Union has claimed to ban the sale of all ICE cars in 2035 and transform them into EVs rapidly [21].

Greenhouse Gases emission has been reduced, especially in CO<sub>2</sub>, NO<sub>x</sub>, and PM 2.5 concentrations, mainly from burning fossil fuel and using combustion engines in cars. The application of HFCVs has benefited on total GHG emission level by 35.8%, showing exceptionally good performance in GHG emission reductions. A study has found that each hydrogen-powered electric vehicle could benefit from GHG emission reduction by 1,129 tons. The development of HFCV represents the best solution for the future economy and electric vehicle industries [22].

##### **4.1. Barriers to hydrogen fuel cell**

Although hydrogen fuel cell shows good performance, challenges exist if the world wants to better develop the hydrogen economy in the future. It is still difficult to overcome such barriers to hydrogen fuel because they are technological issues. Finding solutions and focusing on the disadvantages of HFCs would help the world widen the market.

First, it has safety issues because most new vehicles are higher in voltage, which has a greater possibility for electric shock. New vehicles from the industry could reach up to 42V in the current standard, compared to those old vehicles which only have 14 V. Some newer could run to about 350V under a higher current stage, there will be great danger of electric shock and is fatal to human life [14]. Hence, the EV industry needs technological innovation to ensure their vehicles hold high voltage supply for adapting HFCs and even for future applications because there are still many old and low-voltage vehicles in the market.

Second, hydrogen storage is a big question due to its low density and ease of dispersing; hydrogen storage is a big issue, especially for mobile applications such as long-distance trucks and buses. Technology barriers still exist because current technology cannot maintain long-time storage. Industries use physical-based and material-based approaches to store hydrogen by compressing it into gas, liquid or solid, and even chemisorption or physical sorption. But it is still difficult to store hydrogen to supply higher demand and long-distance usage, or even for stationary storage [23]. Also, storage vessels' reliability needs improvements because current technology would damage vessels and cause hydrogen leakage.

Moreover, material-based hydrogen storage technology is still in the early stage. Its long-term effectiveness and viability need monitoring, and uncertainty exists if largely used in hydrogen storage. Meanwhile, hydrogen delivery is also a challenge because costs are higher in preventing or minimizing hydrogen leakage; maintaining its purity and energy efficiency are also exceedingly difficult due to hydrogen's natural characteristics. It requires an environment with high pressure and low temperature; otherwise, greater possibility for dispersal and flaming. However, the higher temperature might damage hydrogen systems such as damaging pipelines and mechanisms of carbon fibers, causing contamination during delivery; also, it might cause liner blistering for pressure vessels [24]. Moreover, the public must understand and accept this advanced technology because it is still at an early stage and sounds incredibly young.

Moreover, the world lacks hydrogen refueling infrastructures. There are about just 400 hydrogen power stations operating today, and they are dispersed over several countries. The world has planned to create more by 2030, around 1000. At the time, typical refueling infrastructure has a 100-350 kg/day capacity, and larger stations with a capacity of 500 to 1500 kg/day are under development. But it is still inefficient in current refueling network systems, costs are higher, and it always needs strong and durable policies to support its development. The main challenge is creating codes for the joint developments of refueling networks and hydrogen-powered electric vehicles. Many approaches have been used in creating refueling stations, and their numbers, size and locations, joint development of refueling systems, and HFCVs are still a question because both are at younger stages [25]. National and regional levels of hydrogen refueling networks are needed to support the demand and market of hydrogen fuel cell vehicles. It requires planning and coordination among government, industry, and investor stakeholders.

## **4.2. Current applications of hydrogen fuel cell**

### **4.2.1 On-road HFCVs**

HFC has been applied to small transportation such as on-road vehicles, passenger cars and duty trucks. Currently, there are two mainstream HFC electric vehicles in the market. The Toyota Mirai and Hyundai Nexo are leading the industry, but more hydrogen-powered vehicles will be on the market then. Tesla has claimed to transform from battery-based cars to hydrogen-powered vehicles between 2024 to 2025 on Model 2 new cars. For example, China has emphasized the development of renewable energy and environmental sustainability in 2020. Chinese government proclaimed a new policy to boost energy development and applications of hydrogen fuel technology. Also, China takes place at the world's largest hydrogen producer country. The government has announced the First-Five Year Plan for developing the hydrogen economy between 2021 to 2035. There were about 8400 FCVs in China in 2020; most were buses and heavy-duty vehicles. The nation has claimed to have 50,000 fuel cell vehicles by 2025 and about 300 hydrogen refueling stations over the country [26].

### **4.2.2 Marine vehicles**

Increasing energy demand has led the offshore industry to transform to renewable fuel sources. Hydrogen source is very efficient and environmentally friendly in maritime transportation. The European Union has invested 7 million euros in one FLAGSHIP project, and the European Maritime Safety Organization (EMSA) claimed to cut about 40% of CO<sub>2</sub> emissions from the 2005 level to 2050. At the time, HFCVs are used as the main power forwarder of marine vehicles such as applications in commercial ships, trip boats, submarines since 2003, high-speed H<sub>2</sub> Ferry and passenger ship Nemo H<sub>2</sub> from 2012 etc. [27]. It has been used for several years along with population growth and higher energy demand; hydrogen fuel and HFCVs applications have become the most efficient and effective approach to sustainable development.

### **4.2.3 Trains**

HFCVs have been applied on commercial passenger trains, although few countries currently run hydrogen-powered trains. The Coradia iLint is the first hydrogen-powered train in the world, it appeared in 2016 at the InnoTrans in Berlin, and its application started in 2018, transforming from

diesel-powered to hydrogen technology for commercial passenger trains. Also, HFCVs are being applied in Southern Italy on passenger trains. From the analysis that its fuel energy efficiency reached about 47% more and facility efficiency at 50%. Moreover, China will start to run its first HFCV train for trial in 2021. Although hydrogen-powered trains are being used in just a few countries, it shows higher energy and operation efficiency performance, and many countries are developing their HFCV trains and planning for public use [28].

#### 4. Power generations (hydrogen power plants):

HFCV's application in power generation is a new concept. Korea has the world's largest hydrogen fuel cell power plant -The Daesan power plant originated in 2015. But there will be more hydrogen-powered generation in the future, targeting the goal of carbon-neutral and a low-carbon economy [29].

#### 5. Aircraft

Hydrogen-hybrid powered aircraft works the same as applications on vehicles. It requires hydrogen as a power source for a battery like a fuel cell, which is currently not universally used in passenger planes because some have developed unmanned aircraft [30]. The study emphasized that the application of HFCVs on commercial aircraft will enter the market in the next two decades, and development will last about 15 to 20 years for commercial aircraft applications. Also, Airbus has revealed three concepts, one of which will apply to aircraft services in 2035. It designs to use liquid hydrogen as the fuel source to power the aircraft to achieve zero-emission.

### 5. Conclusions

Hydrogen fuel cell technology is the trend for future development. It is the cleanest way to achieve carbon neutrality by 2050. However, hydrogen is hard to extract, and platinum is limited. Substitute sources for catalyst use are studied, and industries are expected to have Pt-free catalysts applied to FCs. This research found that HFC technology works better on electric vehicles than on battery-based cells. However, it has barriers that need to overwhelm, including hydrogen storage and delivery, the establishment of refueling networks etc. It is a world challenge because it requires technological innovation, but it has expected to make progress in the future. Currently, HFCs are not largely devoted to the market, industries will gradually apply HFCs to EVs and other fields, and countries are trying to promote HFCs application to the public through rising incentives for buying electric vehicles. In this research, the efficiency and effectiveness of the hydrogen fuel cell are defined; at once, the world is planning to input more hydrogen fuel cell-powered E-cars into the market to thoroughly replace internal combustion and battery-based vehicles. By 2035, the world is expecting the widespread of fuel cell-powered electric vehicles and their mature application in other fields.

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